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HYDRAZINE FUELED AIRCRAFT STARTER FEASIBILITY DEMONSTRATION

ROCKET RESEARCH CORPORATION
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REDMOND, WASHINGTON 98052

MARCH 1977

FINAL REPORT FOR PERIOD 30 MAY 1975 - 31 MARCH 1977

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AIR FORCE AERO-PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This report has been reviewed by the Information Office, (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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This program was initiated with FY75 Aero Propulsion Laboratory Director's Funds.

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The purpose of this program was to determine the feasibility of converting an aircraft jet engine starter that is normally powered with an 8LBm solid propellant cartridge (type MXU4A/A), to an equivalent liquid monopropellant-fueled device utilizing state-of-the-art hydrazine technology, the single most difficult development constraint being that the complete hydrazine system must package within the space normally occupied by the MXU4A/A solid propellant cartridge in the starter breech. next page

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The feasibility of packaging a hydrazine fueled cartridge in the existing solid propellant breech volume and meeting performance requirements was successfully demonstrated using a breadboard hydrazine system in conjunction with actual cartridge starter hardware.

All major program objectives were achieved including: a) Development of a catalytic decomposition chamber and hydrazine blend which will reliably start and operate at temperatures down to -65°F; b) demonstration that the hydrazine cartridge duplicates or exceeds the output energy available from the existing solid propellant cartridge; c) demonstration of particulate-free exhaust products; and d) completion of a preliminary design of a flight configured hydrazine cartridge which will fit within the existing breech.

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SECTION I
INTRODUCTION AND SUMMARY

This report describes the work performed at Rocket Research Corporation (RRC) during the period starting May 30, 1975, and ending March 31, 1977, under USAF Contract F-33615-75-C-2027 which was granted by the Air Force Systems Command, Aeronautical Systems Division/PPMNB, Wright Patterson AFB.

The purpose of the program was to determine the feasibility of converting an aircraft jet engine starter that is normally powered with an 8-lbm solid propellant cartridge (type MXU4A/A), to an equivalent liquid monopropellant-fueled device utilizing state-of-the-art hydrazine technology, the single most important and most difficult development constraint being that the complete hydrazine system must package within the space normally occupied by the MXU4A/A solid propellant cartridge in the starter breech.

As discussed herein, and summarized in the Conclusions Section, page 133, RRC has successfully demonstrated the feasibility of converting the cartridge starter to operate with hydrazine-based propellant, and the resultant system can be packaged within the space normally occupied by the MXU4A/A solid propellant cartridge in the starter breech.

The feasibility demonstration program was conducted in two phases. The initial phase included analysis and design activities which resulted in a preliminary design drawing of a flight concept version of the hydrazine-fueled starter. The hydrazine conversion package includes a starter breech base-mounted gas generator (catalytic decomposition reactor), an expendable fuel cartridge which contains sufficient hydrazine-based fuel for the worst-case (-65°F) start condition, and a pressurization subsystem that is used to pressurize the fuel cartridge for fuel expulsion during starter operation. A planning document was then prepared for the conduct of the experimental (Phase II) portion of the program.

After contractor's review of the flight concept preliminary design drawing and the Phase II planning document, prototype hardware was fabricated; and the basic feasibility of starter operation in the "hydrazine mode" was successfully demonstrated.

Based on the results of Phase I/II activities, a Final Flight Concept Preliminary Design was completed which incorporated all the technical advancement provided by this effort. This design is shown on page 4.

The results of the Phase I/II activities are summarized in the following subsections and discussed in detail in the remaining sections of this report.

1.1 PHASE I SUMMARY

Initial analysis and preliminary physical component layout drawings prepared during the proposal phase of the program indicated that there should be sufficient space available within the breech envelope of the solid-propellant-fueled jet engine starter to package a complete hydrazine-fueled gas generating subsystem which would be capable of providing cartridge starter performance equivalent to that obtained with the MXU4A/A cartridge.

The hydrazine-fueled starter would be capable of operating over an ambient temperature range of -65 to +160°F, in any attitude, while delivering energy rates and total energy equivalent to the MXU4A/A solid propellant cartridge.

During Phase I, detailed design layouts were developed for each component in the hydrazine-fueled gas generating system; and a conceptual preliminary design drawing of the hydrazine-fueled starter was prepared for contractor's review with the basic requirements established for the system. Phase I was concluded by preparing a planning document for the following experimental demonstration test program (Phase II).

1.2 PHASE II SUMMARY

Early Phase II activities included the design and fabrication of a subscale hydrazine-fueled gas generator, the buildup of a breadboard fuel supply system, and the installation of a government-furnished universal jet engine starter test stand.

Initial subscale gas generator testing verified the adequacy of the proposed flight concept gas generator design approach.

Baseline starter operating characterization testing was then conducted using a model STU13A/34 starter and MXU4A/A solid propellant cartridges. The "cartridge-mode" operating characteristics of the starter were measured, at RRC, by operating the starter on the inertia wheel type universal starter test stand. Multiple cartridge starts were conducted at ambient temperatures ranging from -65 to +160°F. This test series defined starter output shaft terminal speed and time to terminal speed characteristics as a function of soak temperature in the cartridge mode.

Hydrazine-fueled starter testing was then initiated by installing the prototype flight concept gas generator in the breech base of the STU13A/34 starter which was then supplied with pressure-regulated fuel from a breadboard fuel supply subsystem.

The performance of the hydrazine-fueled starter was monitored with the universal starter test stand for direct comparison with the baseline "cartridge-mode" test results. Additionally, fuel consumption per start cycle was measured directly from the run tank in the breadboard fuel supply system.

The hydrazine-fueled starter was operated 24 times with the TSF-1 candidate fuel blend to demonstrate a minimum gas generator life capability of at least 20 full power start cycles. Four firings were conducted at -65°F soak conditions, two firings at +160°F, and the remaining 18 firings were at ambient.

Eight additional hydrazine-fueled start cycles were then conducted with the TSF-2 candidate fuel blend. Three firings were conducted at -65°F soak conditions, three at +160°F, and two at ambient.

A review of the fuel consumption per start cycle with the TSF-1 and TSF-2 fuel blends indicated that the TSF-1 fuel blend could not be packaged in the space available in the starter breech, and the space available would be marginal with the TSF-2 fuel blend. Additional analysis was then conducted to determine what changes, if any, could be made to the original Phase I flight concept design layout to increase the space available within the breech envelope for fuel storage. This analysis indicated that adequate additional fuel storage volume could be obtained by revising the fuel pressurization subsystem from the original hydrazine-fueled configuration to a solid propellant pressurization subsystem.

A breadboard version of the proposed solid propellant fuel pressurization subsystem was subsequently designed, fabricated, and evaluated; and the hydrazine-fueled starter was successfully operated while receiving TSF-2 fuel from the breadboard solid propellant fuel pressurization subsystem.

The final version of the hydrazine-fueled jet engine starter flight concept design is shown in the isometric drawing of Figure 1 and described in detail in Section IV of this report.

Referring to Figure 1, the major components of the hydrazine conversion package include a gas generator and a liquid fuel cartridge. These components are contained within the starter breech in the space normally occupied by the MXU4A/A, 8-lb solid propellant starter cartridge.

The gas generator is an assembly of eight small catalytic decomposition reactors arranged in parallel and manifolded to a central, common liquid fuel supply fitting. The gas generator is adapted to the cavity available in the starter breech base. The gas generator would remain in the breech base throughout its useful life, estimated at 400 to 800 starter operating cycles.

The liquid fuel cartridge is an expendable item that would be replaced prior to each starter operating cycle per the procedures currently in effect for the MXU4A/A solid propellant cartridge. The liquid fuel cartridge interfaces with the gas generator fuel supply fitting through a burst-disc-sealed fuel outlet port. The hydrazine-based liquid fuel supply is retained by an integral elastomeric bladder which is contained within the fuel cartridge shell. Bladder retention of the liquid fuel charge will allow the starter to operate in any attitude. The fuel cartridge contains sufficient hydrazine-based liquid fuel for one starter operating cycle at any temperature in the required -65 to +160°F operating range. The fuel cartridge also includes a small solid propellant pressurization subsystem that is used to pressurize and expel the liquid fuel charge through the gas generator when the starter is operated. The solid propellant subsystem is initiated electrically, and its power connection interfaces with the electrical connector that is currently installed in the breech cap for initiating the MXU4A/A, 8-lbm solid cartridge.

The Phase II test program has successfully demonstrated the basic feasibility of operating a jet engine starter with hydrazine-based fuel blends. Hydrazine starter performance equivalent to solid propellant-fueled starter performance has been demonstrated at -65, ambient, and +160°F soak conditions with a worst-case fuel consumption (-65°F start) that is compatible with the space available within the cartridge starter breech envelope for liquid fuel storage.

HYDRAZINE-FUELED STARTER — FLIGHT CONCEPT

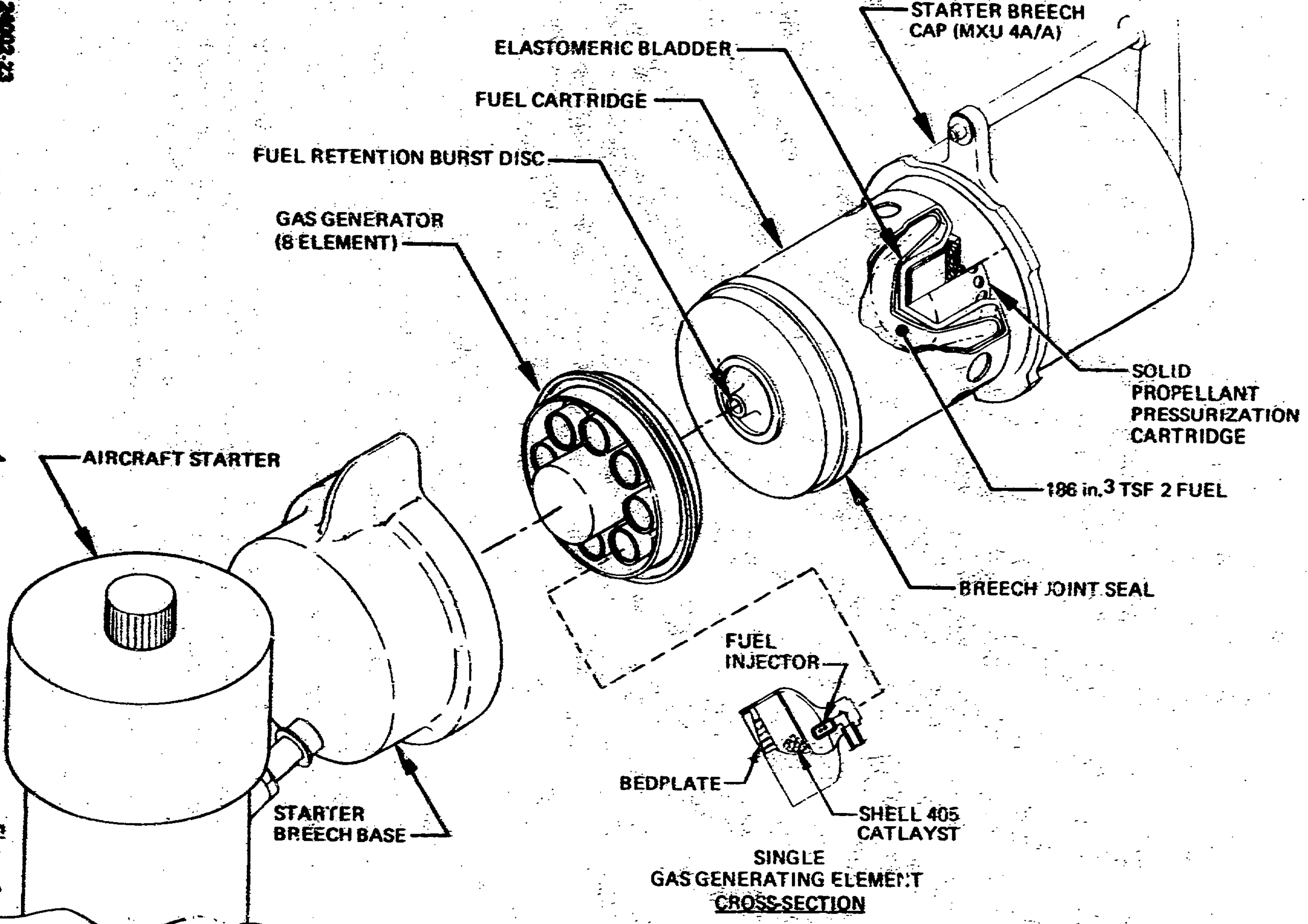

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Figure 1

SECTION II
PHASE I – CONCEPTUAL DESIGN

Three months were allotted at the beginning of the program for Phase I system studies, preliminary design analyses, and program planning activities. The major objectives of the Phase I task were as follows:

a. Prepare a preliminary design layout of the hydrazine system concept that could be used in a flight version of the hydrazine-fueled starter.

b. Predict the operating characteristics of this system and a hydrazine-fueled starter.

c. Prepare for a review of the safety and maintainability aspects of the hydrazine-fueled starter.

d. Prepare a program plan to describe the proposed experimental test program (Phase II) to determine and/or demonstrate the feasibility of converting a customer-furnished solid propellant-fueled jet engine starter to hydrazine.

A formal presentation of the Phase I material was conducted at the end of the 3-month study period for contracting agency review and approval prior to proceeding with the Phase II hardware fabrication and test program. The major elements of the Phase I task are discussed in the following subsections.

2.1 GENERAL APPROACH

The general approach to the design of the flight concept version of the hydrazine fueled starter was to use existing technology to the maximum possible extent. Unique system requirements were primarily associated with the extremely limited packaging space available for the hydrazine subsystem and the requirement for system operation at -65°F soak conditions. The Phase I program elements are discussed below.

2.2 FUEL SELECTION

The ideal fuel for monopropellant hydrazine conversion of the cartridge starter is anhydrous hydrazine (neat hydrazine). Unfortunately, the freezing point of the anhydrous hydrazine is approximately +35°F and is inconsistent with the requirement for system operation over a temperature range that extends from -65 to +160°F.

Neat hydrazine could be considered if sufficient electrical power were available to power system heaters to prevent fuel freezing at low system soak temperatures. However, the lack of power availability and the undesirable complication of system heaters eliminate this approach.

There are a number of additives and combinations of additives that may be used to depress the freezing point of anhydrous hydrazine. These additives are identified and discussed in the following paragraphs.

2.2.1 Hydrazine Additives

Candidate freezing point depressant additives for hydrazine include water, ammonia, hydrazine nitrate (HN), monomethyl hydrazine (MMH), ammonium thiocyanate, hydrogen cyanide, and hydrazinium azide.

One of the preliminary considerations in the selection of additives to reduce the freezing point is the type of decomposition chamber to be employed in the system. Since the hydrazine-fueled starter will require a spontaneous type catalytic reactor with long life and multiple restart capability, any carbon containing additives must be eliminated from consideration as viable candidates since additives in this family will deposit carbon on the active sites of the catalyst and reduce the effective activity of the catalyst below that required for repeated restart capability. This reduces the candidate additives to water, ammonia, and hydrazine nitrate. The azide propellants offer no advantages over nitrated propellant, the safety characteristics are inferior, and gas generator tests indicate an order of magnitude increase in catalyst loss rate over the nitrate propellants.

A second consideration in the selection of additives is their effect on the energy content of the resultant fuel mixture. Water and ammonia will reduce the energy content of the blend, and hydrazine nitrate will increase the energy content.

2.2.2 Binary Propellant Mixtures

Binary mixtures of hydrazine and water, ammonia, or hydrazine nitrate can be evaluated in gross terms for this application as follows:

1. <u>Hydrazine/Water</u>

   A -65°F freezing point is obtainable with reasonable fuel mix energy content.

2. <u>Hydrazine/Ammonia</u>

   A -65°F freezing point requires approximately 64% ammonia by weight; the energy content of the resultant mixture is not adequate for this application, and this high percentage of ammonia makes it very marginal that decomposition can be reliably obtained. Additionally, the high vapor pressure of an ammonia additive would increase the complexity of fuel mix operations and complicate the design of the fuel cartridge; therefore, ammonia is not considered as a viable candidate for a freezing point depressant for this application.

3. <u>Hydrazine/Hydrazine Nitrate</u>

   The maximum freezing point depression obtainable with this mixture is 0°F when consideration is given to selecting a mixture which is not in a shock-sensitive range. Therefore, a binary mixture of hydrazine nitrate cannot be considered for this application.

2.2.3 Ternary Propellant Mixtures

Hydrazine can be combined with various percentages of water and hydrazine nitrate as a ternary blend to satisfy the -65°F freezing point requirement. Additionally, the resultant ternary mixes have a greater energy content than the hydrazine-water mix previously discussed and are stable compounds which are not shock sensitive.

2.2.4 Propellant Selection

The above review of the additives available and a consideration of the long-life requirement for the catalytic gas generator, with multiple restart capability, have resulted in the selection of water, or a combination of hydrazine nitrate ($N_2H_5NO_3$) and water, as the preferred freezing point depressant additives for this application.

Rocket Research Corporation selected three candidate turbine starter fuel (TSF) mixtures for additional analysis. The composition of these fuel mixtures is summarized in Table 1.

Table 1
COMPOSITION OF CANDIDATE APU STARTER FUELS

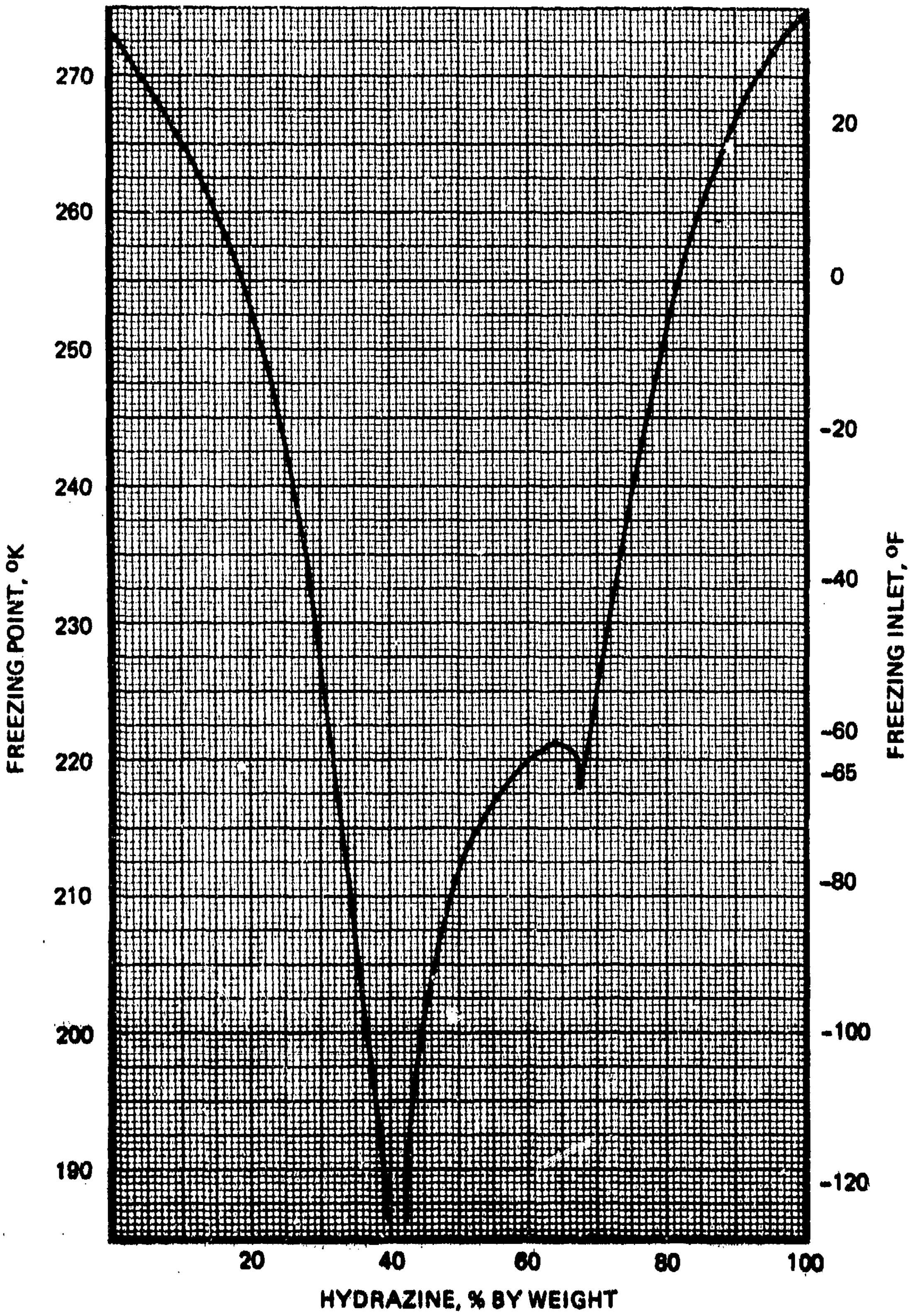
Fuel Mix Identifier	Composition % by Weight		
	N_2H_4	$N_2H_5NO_3$	H_2O
TSF-1	60	21	19
TSF-2	58	25	17
TSF-3	68	–	32

Figure 2 depicts the freezing point characteristics of binary mixtures of water and anhydrous hydrazine as a function of the percentage by weight of hydrazine in the mix. The required -65°F freezing point may be obtained in fuel mixtures containing 32, 57, or 68 percent hydrazine. A hydrazine/water mixture containing 68 percent hydrazine (TSF-3) was selected to maximize the energy content of the fuel mix.

Freezing point depression to -65°F can be obtained with any ternary mixture of hydrazine, hydrazine nitrate, and water within the boundary established by the dashed envelope of Figure 3 (i.e., outside the shock-sensitive boundary). The energy content of the resultant mixture increases as the mixture becomes richer in hydrazine or hydrazine nitrate content as noted by the superimposed exhaust gas isotherms. The most energetic mixtures lie in a regime that is classified as detonable by the card gap test method.

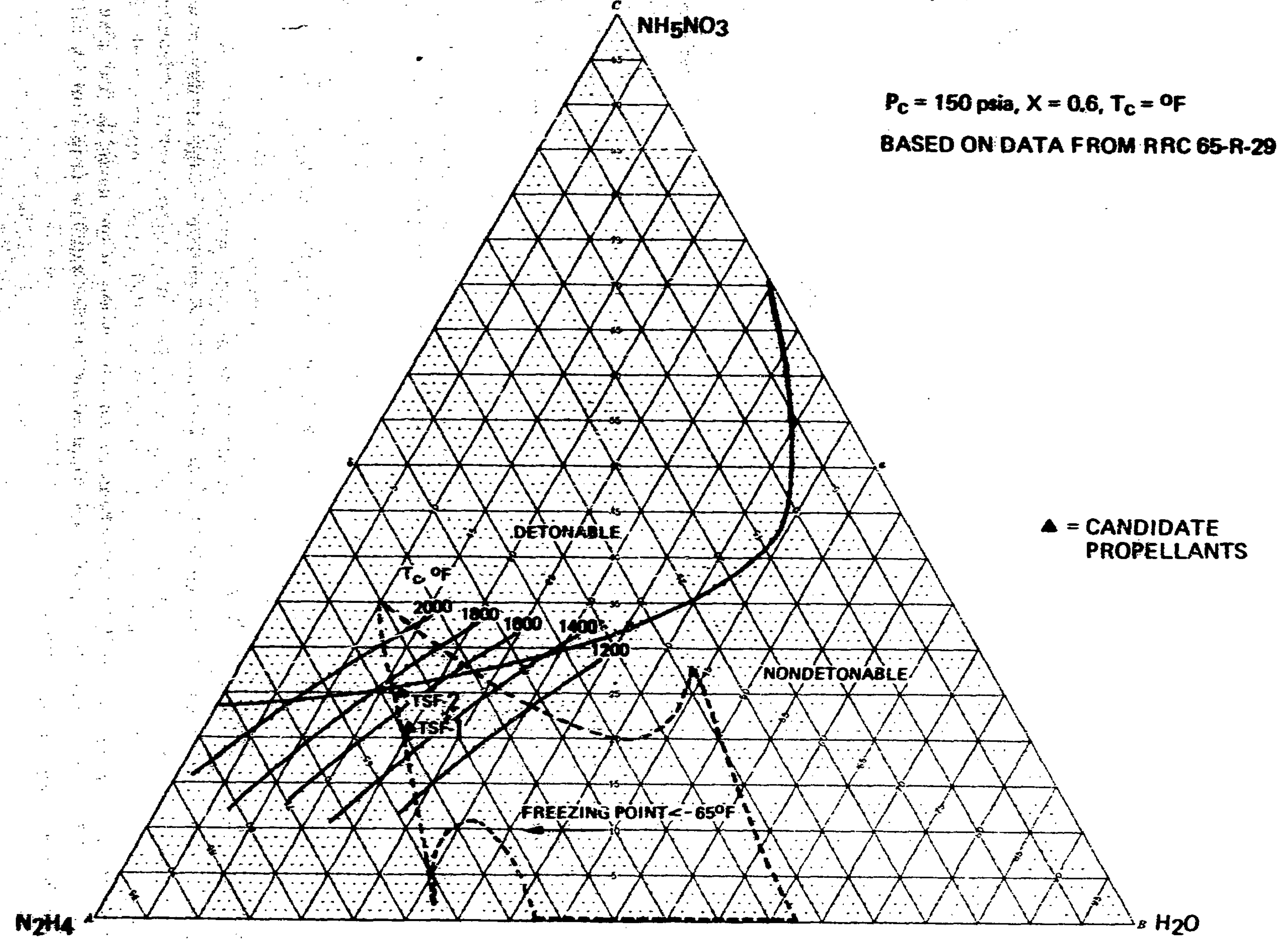
The ternary mixes selected for possible use in this application are shown by triangular symbols on Figure 3. The TSF-2 mix lies within the -65°F freezing point envelope and slightly below the detonable boundary. TSF-1 is also within the -65°F freezing point envelope, with additional margin below the detonable boundary. Therefore, TSF-1 is the least energetic of the two ternary mixes but has improved safety margin.

FREEZING POINT OF HYDRAZINE-WATER MIXTURES



DATA SOURCE – HILL AND SUMNER

CHAMBER TEMPERATURE PROFILE AND -65°F FREEZING POINT ISOTHERM OF HYDRAZINE/HYDRAZINIUM NITRATE/WATER MIXTURES



The liquid bulk density of the candidate binary and ternary fuel mixes can be determined from the data shown in Figure 4. It will be noted that the ternary mixes TSF-1 and TSF-2 are significantly denser than the binary mix TSF-3.

The relatively high bulk density of the ternary mixes and the energy content of the resultant exhaust products will combine to yield the minimum required fuel storage volume for a given cartridge starter operating cycle.

The temperature and the composition of the exhaust gas generated by the decomposition of hydrazine-based fuels is a strong function of the chemical composition of the fuel mix, temperature of the fuel supplied to the gas generator, and certain physical design variables in the decomposition chamber.

Hydrazine fuel may be considered to be decomposed in the gas generator reactor according to the following consecutive reactions:

$$3N_2H_4 \longrightarrow 4NH_3 + N_2 + 144{,}300 \text{ Btu} \tag{1}$$

$$4NH_3 \xrightarrow[\text{cat}]{} 2N_2 + 6H_2 - 79{,}200 \text{ Btu} \tag{2}$$

In the first step of the reaction model, the hydrazine is broken catalytically into ammonia and nitrogen. In the second step, the ammonia formed is dissociated into nitrogen and hydrogen. In the first step, the exhaust products would be slightly toxic due to the presence of ammonia and relatively nonflammable due to the absence of hydrogen. In the second step, which is exothermic, the exhaust gas temperature decreases as the ammonia dissociates into nitrogen and hydrogen, effectively reducing the toxicity of the exhaust products and increasing their flammability due to the presence of hydrogen.

Basically, the control of the flow variables and the geometry of the gas generator control the degree of completion of the second step of the reaction process for a neat hydrazine fueled gas generator. This provides the designer a means of controlling the exhaust gas temperature and composition of the exhaust products. Equations (1) and (2) may be combined as follows for calculation purposes:

$$3N_2H_4 \xrightarrow[\text{cat}]{} 4(1 - X)\,NH_3 + 6XH_2 + (2X - 1)\,N_2 + [144{,}300 - X(79{,}200)] \text{ Btu} \tag{3}$$

where X = fraction of NH_3 dissociated.

For the fuel mixes of interest, equation (3) may be modified to account for the addition of water and/or hydrazine nitrate, and all of the properties of the resultant exhaust gas may be determined for a meaningful range of ammonia dissociation (X) over a fuel supply temperature of -65 to +160°F. Table 2 summarizes the thermochemical characterization of the candidate fuel mixes for study. Table 3 summarizes the exhaust gas composition of the candidate propellant blends as a function of ammonia dissociation.

DENSITY OF HYDRAZINE/HYDRAZINIUM NITRATE/WATER TERNARY MIXTURES, g/cm^3 AT (298°K) 77°F

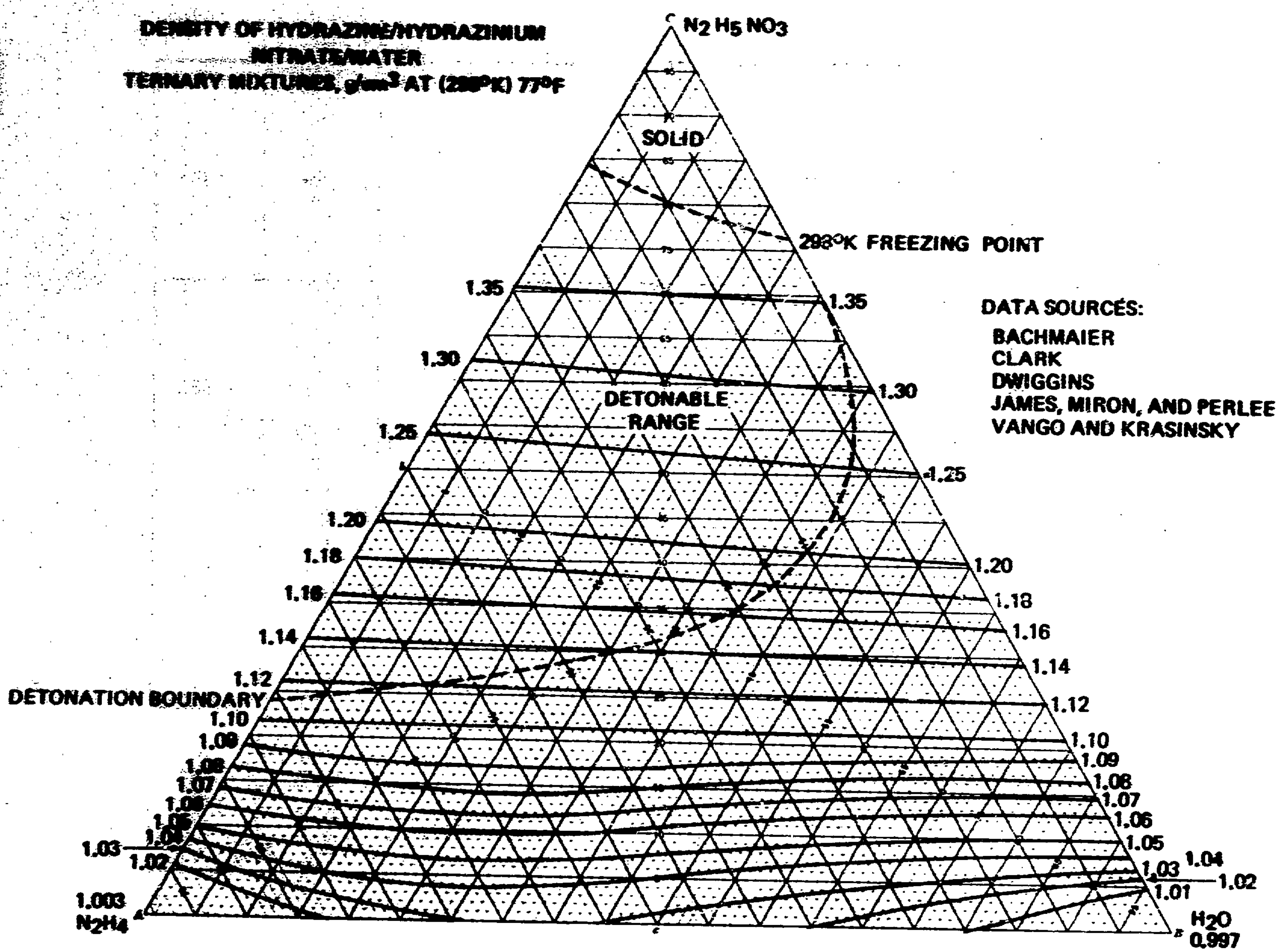


Figure 4

Table 2
THERMOCHEMICAL PERFORMANCE CHARACTERISTICS

Fuel Mix	Composition % by Weight			NH_3 Dissociation X	Fuel Supply Temp. °F (T_f)	Gas Temp. °F (T_c)	Molecular Weight ($\bar{M}_c$)	Ratio of Specific Heat Capacities γ_c
	N_2H_4	H_2O	$N_2H_5NO_3$					
TSF-1	60	19	21	0.4	-65	1,594	16.318	1.2486
					+77	1,767	16.318	1.2414
					+160	1,871	16.318	1.2375
				0.6	-65	1,401	15.111	1.2808
					+77	1,576	15.111	1.2723
					+160	1,684	15.111	1.2677
TSF-2	58	17	25	0.4	-65	1,760	16.500	1.2424
					+77	1,929	16.500	1.2361
					+160	2,033	16.500	1.2327
				0.6	-65	1,574	15.310	1.2726
					+77	1,747	15.310	1.2653
					+160	1,853	15.310	1.2612
TSF-3	68	32	—	0.1	-65	980	17.871	1.2426
					+77	1,169	17.871	1.2304
					+160	1,292	17.871	1.2234
				0.2	-65	865	17.011	1.2629
					+77	1,058	17.011	1.2495
					+160	1,182	17.011	1.2418

Table 3

EXHAUST GAS COMPOSITION OF CANDIDATE PROPELLANT BLENDS

Propellant Blend	Ammonia Dissociation %	Exhaust Gas Composition, % by Volume			
		Nitrogen	Ammonia	Hydrogen	Water
TSF-1	40	23.7	24	24	28.3
	60	25.7	14.8	33.3	26.2
TSF-2	40	24.4	23.4	23.3	28.9
	60	20.2	14.4	32.4	26.9
TSF-3	0	13.3	53.2	0	33.4
	20	16.8	38.5	14.4	30.2

Tests conducted by RRC on water/hydrazine mixtures indicate that no ammonia dissociation is obtained below 1,000°F exhaust gas temperature. For the water/hydrazine blend, ammonia dissociation values of zero to 20 percent are expected. For the nitrated propellant blends, tests on other RRC programs have indicated ammonia dissociation values of 40 to 60% are to be expected with reasonable bed lengths.

2.2.5 Safety

The general safety guidelines for handling hydrazine and hydrazine water blends are well established and readily available. The safety and handling characteristics of hydrazine/hydrazine nitrate blends are often questioned from the following two aspects:

a. Detonability or shock sensitivity since a limit exists on the amount of hydrazine nitrate which may be added before the propellant does become sensitive

b. Nitrate crystal formation due to inadvertent spillage.

A propellant mixture 24% hydrazine nitrate and 76% hydrazine has been extensively characterized for safety and handling characteristics. The following summarizes the results of safety tests to which this mixture has been tested:

a. The propellant cannot be exploded by shock, friction, or electrical discharge (USBM IC 8452).

b. Closed tanks containing hydrazine blends normally burst without exploding when exposed to bonfires (JPL TR 32-172).

c. Impact of 20 mm incendiary ammunition or 0.3-caliber bullet did not cause explosions (JPL TR 32-172).

d. Negative results with following JANNAF/ICRPG tests.

(1) Drop weight test
(2) Card gap test
(3) Trauzl block test
(4) Detonation propagation test
(5) Adiabatic compression test

As noted, all of the above safety tests gave negative results, indicating good handling and safety characteristics of this blend. Addition of water to hydrazine/hydrazine nitrate blends for the TSF-1 and TSF-2 propellants) will improve the handling characteristics since water acts as a diluent.

In conjunction with a previous RRC contract, tests were conducted on the hazard potential resulting from an undetected spill or propellant residuals in an incompletely emptied tank. The majority of the simulated spill tests were conducted with the 24% HN binary mixture, which is considered more difficult to handle than either TSF-1 or TSF-2. Samples of propellant with constant surface area were exposed to the atmosphere under varying environmental conditions, and the propellant was analyzed after repeated time intervals. The data in Figure 5 shows that both with stagnant air and with air velocity of 50 feet/min, the propellant picked up water from the air because it is hygroscopic. The composition barely touched the detonable range between 2 and 4 hours after initiation of the test and then moved toward the inert water corner of the ternary system.

Subsequent tests were conducted in a closed system under closely controlled conditions with constant relative humidity. The apparatus shown in Figure 6 was used for this test. It consisted of a constant humidity chamber with a constant humidity solution composed of sulfuric acid and water. The constant humidity solution served a dual purpose: first, it maintained a constant relative humidity of water in the chamber regardless of ambient temperature fluctuation; and, secondly, it immediately removed all hydrazine vapor from the atmosphere. The test must be regarded as a more severe test than under actual field conditions because a stationary hydrazine partial pressure above the solution will delay the rate of evaporation considerably.

As shown in Figure 7, detonable mixtures can form under these conditions of increased severity only at humidities below 30%. Even then, it took several days before the curve entered the detonable range. Under practical conditions, a leak would be detected before this time, and corrective action could be taken.

The tests indicate that for the anhydrous 24% HN mixture, detonable mixtures can be formed under extremely dry conditions with a high rate of air exchange. However, this is less likely to happen with the TSF mixtures because these already contain water, and relative humidity in the vicinity of the propellant will always be high. Curves in Figures 5 and 7 pass through compositions similar to TSF without dropping back into the detonable range. It is expected that the initial slope of the curves for 20, 30, 40, or 75% relative humidity will remain the same; just the starting point would be moved to the right by approximately 20 scale units, making it less likely to intersect the detonable range with subsequent evaporation. It must also be emphasized that in no case did the aforementioned evaporation tests with the 24% HN mixture result in the formation of nitrate crystals. The constituents remained completely soluble at 77°F. It is therefore believed that

TWENTY-FOUR HOUR OPEN AIR EVAPORATION TESTS

70°F, 50% RELATIVE HUMIDITY

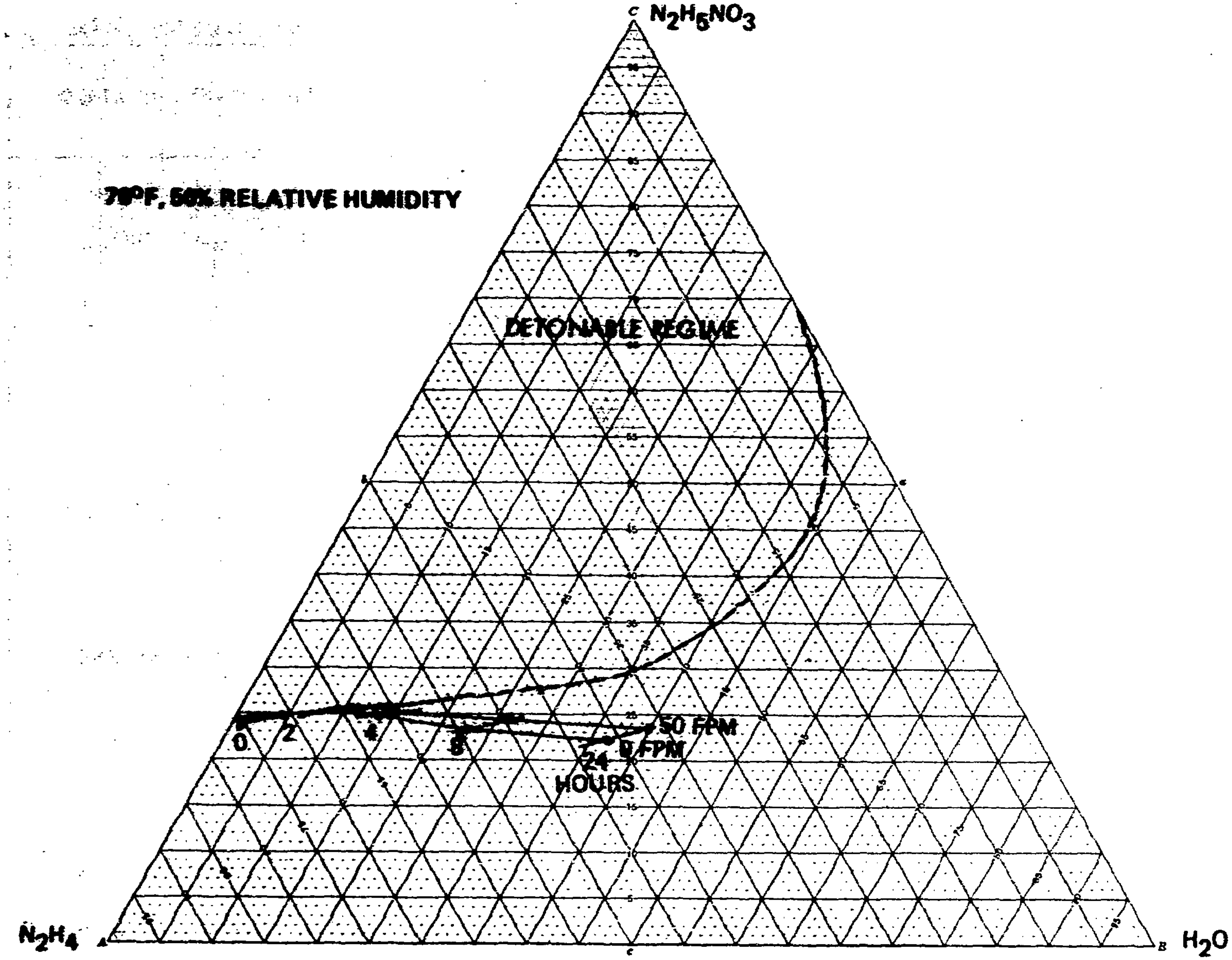
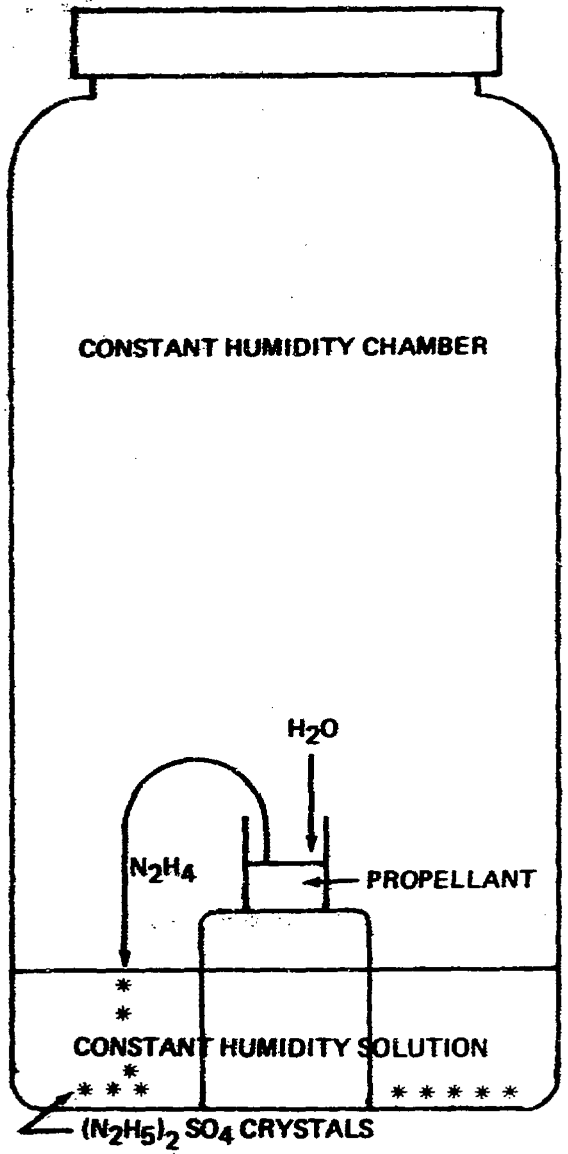


Figure 6

CONTROLLED HUMIDITY TEST



% REL HUMIDITY	COMPONENTS	TIME IN HOURS 0	24	164
5	% N_2H_4, FREE	75.3	74.1	62.5
	% $N_2H_5NO_3$	23.9*	21.5*	33.8**
	% H_2O	0.7	4.4	3.6
40	% N_2H_4, FREE	75.3	72.6	46.5
	% $N_2H_5NO_3$	23.9*	21.0*	18.5*
	% H_2O	0.7	6.4	35.0
75	% N_2H_4, FREE	75.3	69.6	38.5
	% $N_2H_5NO_3$	23.9*	4.6*	8.3*
	% H_2O	0.7	25.8	53.1

*NONDETONABLE
**ALL LIQUID, NO CRYSTALS

RESULTS OF PROPELLANT EXPOSURE TO CONSTANT RELATIVE HUMIDITY AIR AT 75°F

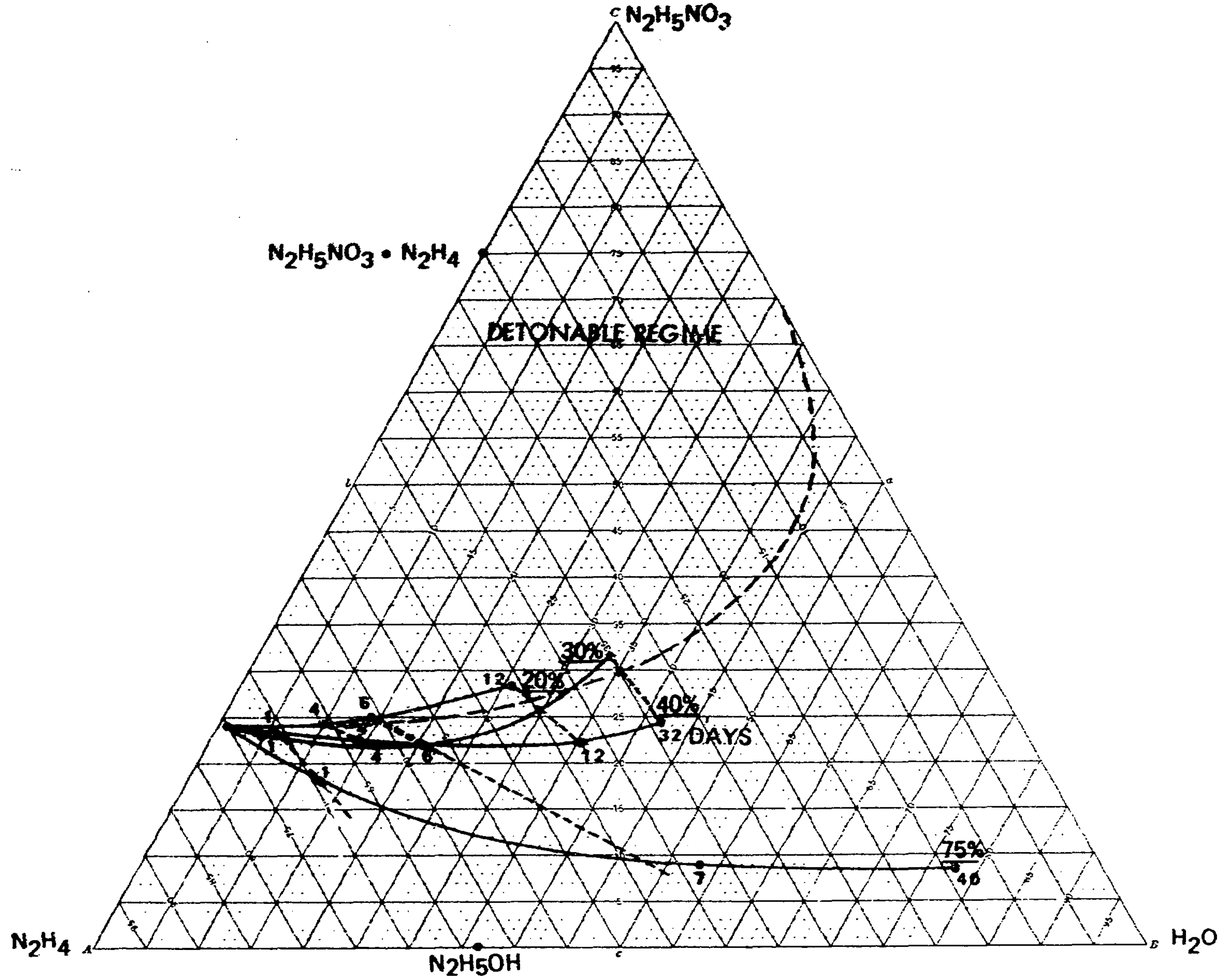


Figure 7

the probability of forming a detonable compound or nitrate crystals with the TSF-1 or TSF-2 propellants is extremely remote.

2.2.6 Cartridge Starter Performance

The performance of the cartridge starter has been analyzed (see paragraph 2.4.2) to evaluate its operating characteristics when the unit is converted to operate on hydrazine-based fuel.

Starter performance is considered adequate and equal to or better than that obtained with the existing solid propellant cartridge when operated with any of the three candidate fuel mixes. No modifications will be required to the turbine portion of the cartridge starter for operation with fuel mixes TSF-1, TSF-2, or TSF-3.

Since TSF-2 has the highest energy density of the three candidate fuel mixes, this mix would be the preferred mix from a gross turbine performance viewpoint. TSF-1 and TSF-3 would be ranked as second and third candidates in that order.

2.2.7 Baseline Fuel Selection

As discussed in paragraph 3.4.2, the TSF-2 fuel blend was finally selected as the baseline fuel for the starter application. Fuel consumption measurements during starter performance testing in the hydrazine mode indicated that the TSF-2 fuel blend was the only candidate fuel that could be packaged in the space available in the breech storage volume that would duplicate the energy available in the solid propellant cartridge at -65°F ambient temperature operating conditions.

2.2.8 Preparation of the Ternary Fuel Mix

There are two fundamental techniques available for blending the ternary TSF-1 and TSF-2 fuel mixes. One method consists of adding water to anhydrous hydrazine followed by the addition of granular industrial grade ammonium nitrate (NH_4NO_3). The second method involves diluting nitric acid (NHO_3) with water and adding the resultant solution to anhydrous hydrazine. Both techniques were evaluated during the Phase II portion of the program as discussed below.

2.2.8.1 Ammonium Nitrate Method

The composition of the TSF-1 fuel mix is ($N_2H_4 + 0.118\ N_2H_5NO_3 + 0.563\ H_2O$). When the fuel mix is prepared by the ammonium nitrate method, the mixing reaction is as follows:

$$\text{Hydrazine + water} \ \overset{\text{heat of hydration}}{\uparrow} \ \text{+ ammonium nitrate} \ \overset{\text{ammonia gas}}{\uparrow}$$

or quantatively:

$$1.118\ N_2H_4 + 0.118\ NH_4NO_3 + 0.563\ H_2O \longrightarrow$$

$$(N_2H_4 + 0.118\ N_2H_5NO_3 + 0.563\ H_2O)_{TSF\text{-}1} + 0.118\ NH_3 \uparrow$$

Thus, with the proper quantities of hydrazine, water, and ammonium nitrate, the TSF-1 fuel mix can be prepared; but the fuel will contain up to 3.6 percent (by weight) of ammonia. This amount of ammonia is considered excessive and must be removed by further fuel processing.

Figure 8 depicts the sparging apparatus that was used by RRC to reduce the ammonia content of the TSF-1 fuel mix to less than 0.4 percent (current limit in anhydrous hydrazine). The fuel was sparged with low pressure gaseous nitrogen for approximately 48 hours in a 55-gallon drum using a glass "tree" to disperse the nitrogen bubbles over a relatively large surface area. After this initial sparging period, fuel sampling and analysis indicated an ammonia content in excess of 1 percent.

A vacuum pump was attached to the vent line, and the sparging process was repeated at a pressure in the drum on the order of 1 psia for 24 hours. Little, if any, reduction in the amount of ammonia content was noted.

The fuel bunker where the sparging was conducted was not heated, and the ambient temperature was in the 35 to 40°F range. The sparging drum was subsequently heated to 70°F, and the vacuum/sparging operation was continued for 10 days with incremental fuel sampling and analysis. The final ammonia content at the conclusion of the 10-day sparge period was 0.35 percent.

2.2.8.2 Nitric Acid Method

When the TSF-2 fuel mix was prepared for the Phase II test program, the nitric acid method was used to avoid the time consuming sparging operation discussed above.

The composition of the TSF-2 fuel mix is ($N_2H_4 + 0.145\ N_2H_5NO_3 + 0.521\ H_2O$). When the fuel mix is prepared by the nitric acid method, the mixing reaction is as follows:

$$\text{Water + acid} \overset{\text{heat}}{\uparrow} \xrightarrow{\text{add mix to}} \text{hydrazine} \overset{\text{heat}}{\uparrow}$$

or quantatively:

$$1.145\ N_2H_4 + 0.145\ NHO_3 + 0.521\ H_2O \longrightarrow$$

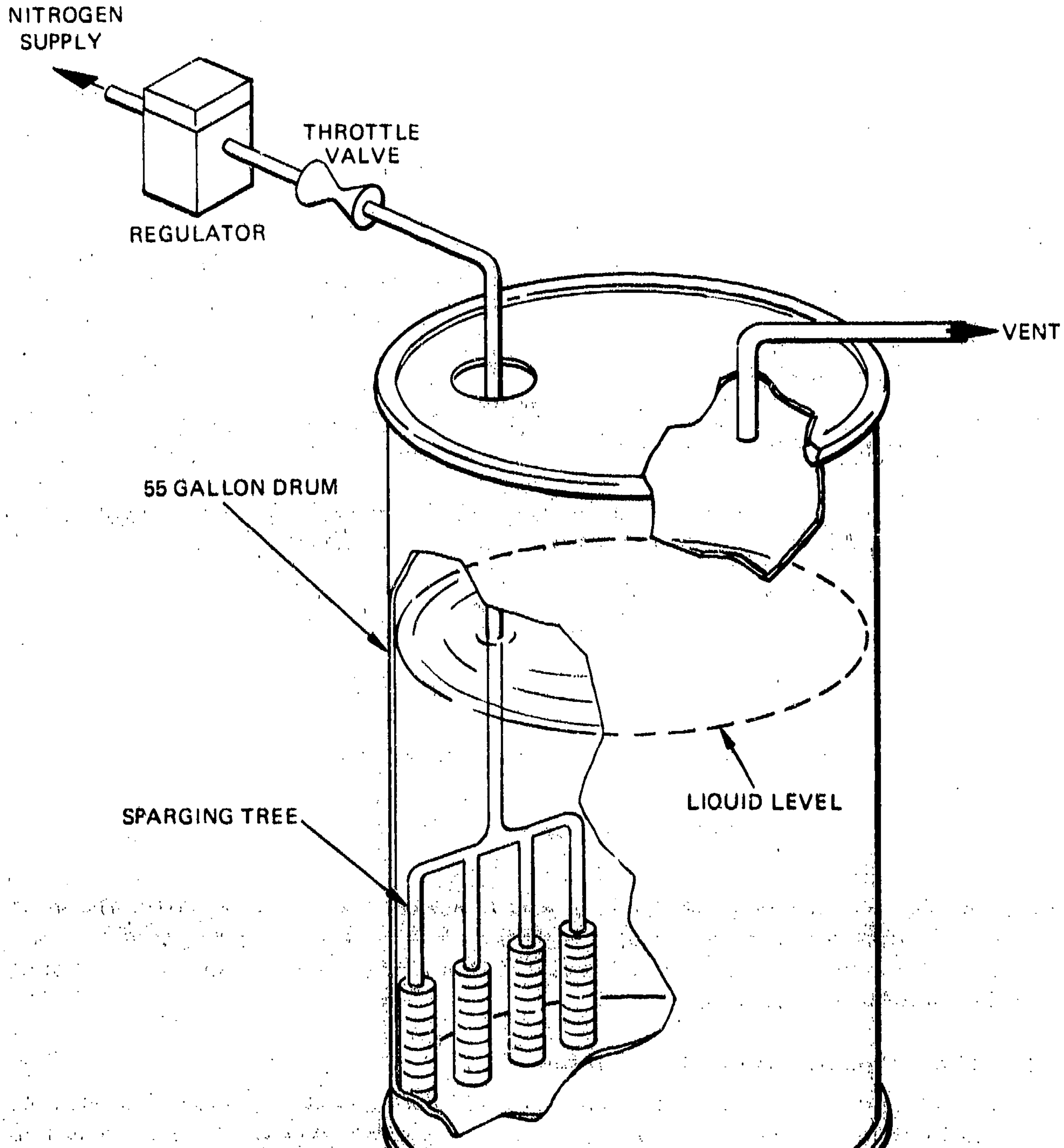
$$(N_2H_4 + 0.145\ N_2H_5NO_3 + 0.521\ H_2O)_{TSF\text{-}2}$$

As noted, the fuel composition by the nitric acid technique is acceptable as mixed. The single constraint in adapting this mixing procedure is the limited allowable rate of adding the diluted acid mix to the anhydrous hydrazine. The dilute acid mix must be added slowly to allow the heat of reaction to dissipate in a safe manner.

2.2.9 Physical Properties of the TSF-1 Fuel Mix

Although not contractually required, RRC conducted a limited physical properties evaluation of the TSF-1 fuel mix to determine the freezing point, low temperature viscosity, and low temperature density characteristics of the fuel blend.

FUEL SPARGING APPARATUS
(AMMONIUM NITRATE MIXING TECHNIQUE)



2.2.9.1 Freezing Point

The TSF-1 fuel mix froze at -95°F and melted, on reheating, at -85°F, providing adequate margin below the required -65°F operating extreme for the starter.

2.2.9.2 Viscosity

The viscosity of the TSF-1 fuel mix was measured by the ASTM D445 method using Cannon-Fenske capillary tubes over a temperature range that varied from -85 to +80°F. The test results are shown in Figure 9.

2.2.9.3 Density

TSF-1 fuel density was measured by the ASTM-D-941-55 method using a Lipkin bicapillary pycnometer over a temperature range that varied from -85 to +77°F. The test results are shown in Figure 10.

2.3 GAS GENERATOR SELECTION

2.3.1 Decomposition Techniques

In broad terms, the decomposition of hydrazine may be carried out by means of two techniques, thermal or catalytic. Early work on hydrazine decomposition was carried out in empty chambers in which the chamber walls were preheated to approximately 1,000°F. This temperature was sufficient such that when propellant was introduced, vaporization and subsequent decomposition would occur. Such techniques required high L* (i.e., chamber volume) in order to complete the decomposition. As the application for hydrazine as a monopropellant grew, catalysts were developed to decrease the decomposition times and minimize required chamber volumes. Initial catalysts were developed which were not spontaneous at ambient temperature, but when heated to 500 to 700°F, exhibited high catalytic activity. Subsequent work resulted in the development by Shell Development Company of a catalyst which would initiate the decomposition at ambient temperature. Development of this catalyst opened up a new broad spectrum for the application of monopropellant hydrazine.

In the past few years many government agencies and industrial firms have concentrated on the development of thermal decomposition techniques for hydrazine-based monopropellants. Such techniques can result in minimizing gas generator costs and, for high production tactical applications, can result in cost savings over catalytic design approaches depending on the size of the device. The ensuing sections discuss in more detail decomposition approaches.

2.3.1.1 Thermal Decomposition

Thermal decomposition of monopropellants is accomplished by preheating the decomposition chamber to temperatures which exceed the decomposition temperature. This heat source provides the initial decomposition, and the heat to sustain the reaction is supplied from the exothermic decomposition reaction. Initiation is accomplished by several means of preheating, which include electrical heating through resistance elements, use of a small solid propellant charge to supply necessary hot gases for preheating, or use of a chemically reactive oxidizer in either liquid or solid form.

VISCOSITY (CENTISTOKES) TSF-1

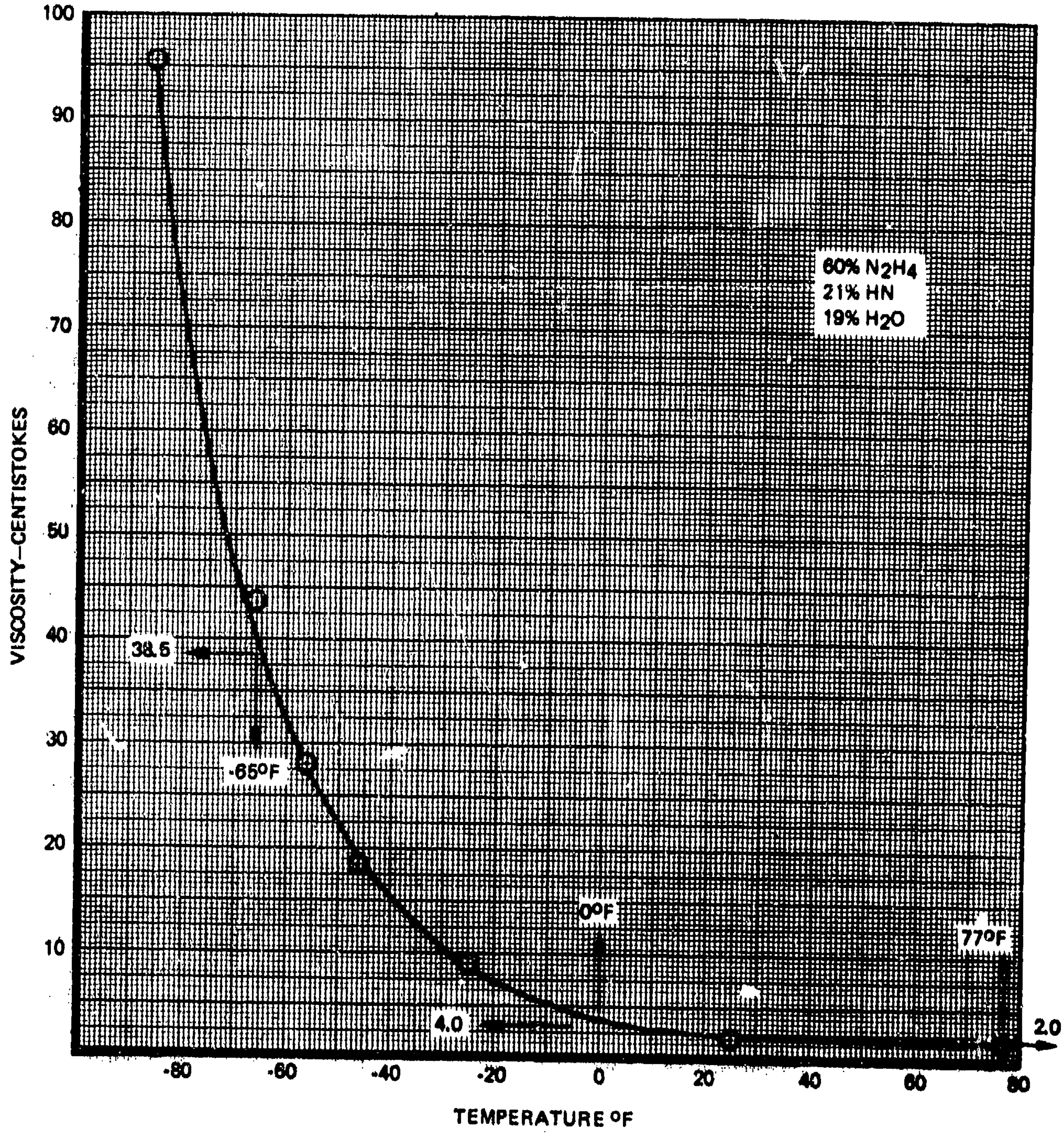


 Figure 9

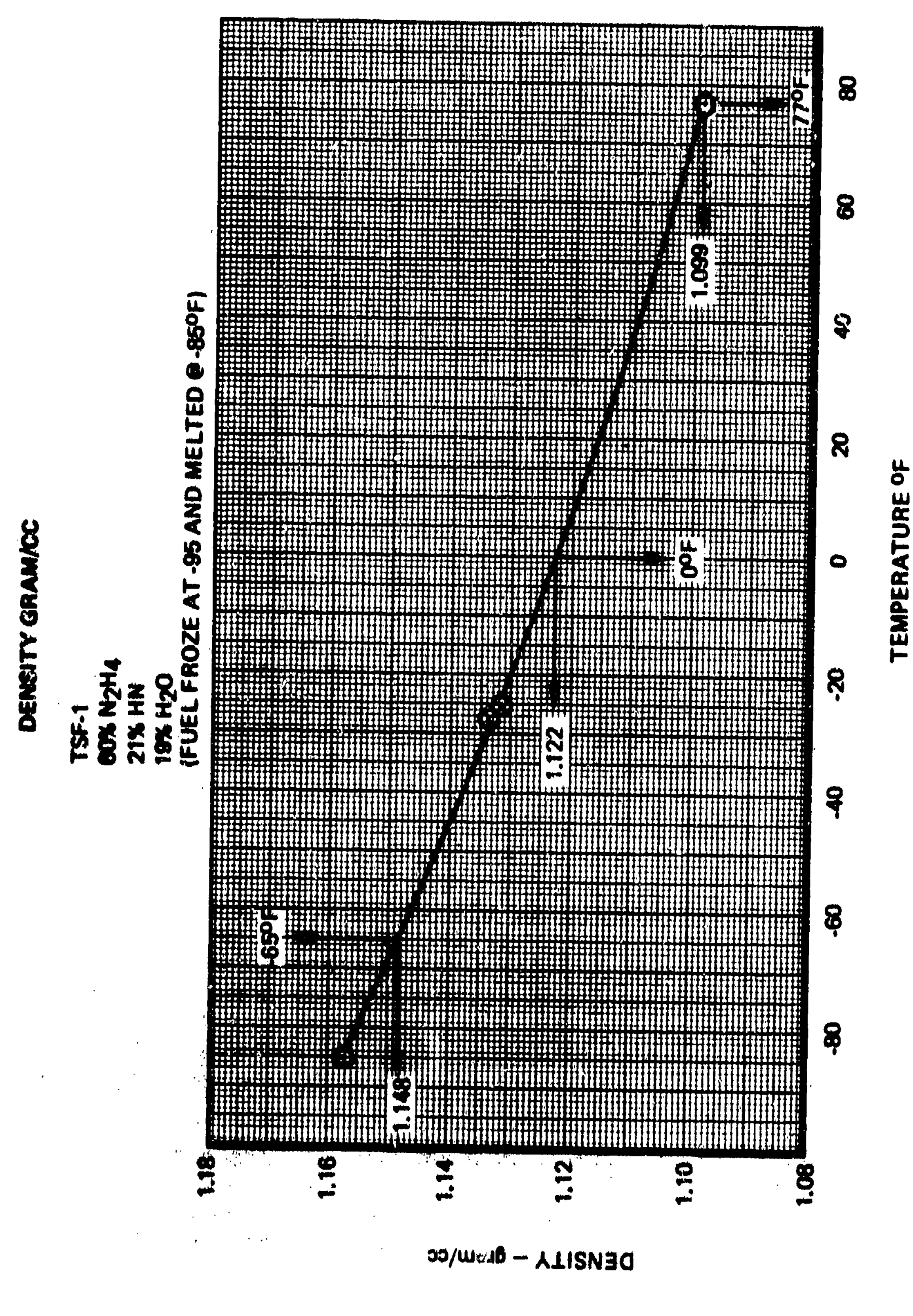

DENSITY GRAM/CC
TSF-1
60% N_2H_4
21% HN
19% H_2O
(FUEL FROZE AT -95 AND MELTED @ -85°F)
-65°F
1.148
1.122
0°F
1.099
77°F
1.18
1.16
1.14
1.12
1.10
1.08
-80
-60
-40
-20
0
20
40
60
80
TEMPERATURE °F
DENSITY – gram/cc

Figure 10

In the thermal bed gas generator, some of the heat from the heat energy liberated by the exothermic decomposition must be used to heat the incoming propellant to its autodecomposition temperature. Consequently, the decomposition zone is stabilized in the thermal bed at a point where the energy required to heat the incoming fuel is equaled by the ability of the hot gas and the thermal bed material to transfer heat into the fuel. As the flow rate or bed loading is increased, the decomposition zone will be established deeper in the bed. If the thermal capacity of the bed is insufficient to heat the incoming propellant to its autodecomposition temperature, the decomposition zone will steadily move out of the bed and flooding will occur. Thus, a desirable thermal bed material should have moderate heat capacity and high thermal conductivity to transfer heat to the top of the bed.

Bed materials commonly employed in thermal bed reactors include wire mesh screens, spherical balls of stainless steel, copper, or ceramic materials, and porous matrices of honeycomb ceramic, fire brick, or foam metals. The most common techniques used for starting thermal beds are either to heat it electrically or to use iodine pentoxide (I_2O_5) in powder form contained at the top of the bed. The I_2O_5 reacts with hydrazine on start to preheat the bed.

The advantages of the thermal bed decomposition technique include potential lower cost, ability to run with carbon containing hydrazine-based monopropellants, and its relative ruggedness compared to catalytic chambers.

The major disadvantages of the thermal bed approach include large chamber volume necessary for decomposition, single failure mode if the auxiliary ignition source does not work, lack of restart capability without an external energy source. The possibility of a misfire if the auxiliary ignition source does not work represents a very serious disadvantage to thermal bed decomposition and on the Space Shuttle program was the one item which led NASA to select a catalytic approach for the hydrazine gas generator APU system.

2.3.1.2 Catalytic Decomposition

Catalysts for the decomposition of hydrazine fall into two classes: those which are spontaneous and initiate decomposition at ambient temperature, and those which must be preheated to varying temperatures before they exhibit sufficient catalytic activity to sustain decomposition.

Catalysts which will not initiate decomposition at ambient temperature typically have to be heated to 500 to 700°F before sufficient activity is obtained to sustain decomposition. These catalysts are typically one or two orders of magnitude less costly than Shell 405 catalyst. Rocket Research Corporation and other organizations have developed several catalysts which fall in this category. Starting is typically obtained by preheating the bed electrically or with a solid propellant or by coating the catalyst with a solid oxidizer.

Shell 405 catalyst represents the best catalyst available to initiate hydrazine decomposition at ambient temperatures. The catalyst has been thoroughly characterized and developed within the industry. Other catalysts have been developed by Shell, RRC, and others which will initiate decomposition at ambient temperature; but their life characteristics are inferior to Shell 405.

2.3.2 Selection of Decomposition Techniques

The previous sections have discussed three techniques for hydrazine decomposition. These techniques are:

a. Thermal bed
b. All spontaneous catalytic beds
c. Nonspontaneous catalytic beds

The above three techniques were numerically evaluated for use in the jet engine starter program against criteria which is important for this application. The results of this analysis are shown in Table 4. It is seen that the spontaneous catalytic approach for decomposition rates is markedly superior to the other approaches. This rating is achieved due to its ability to initiate decomposition without other heat sources, its small envelope and packaging flexibility, its lack of refurbishment requirements between starts, and its ability to very effectively decompose hydrazine/water propellant mixtures.

Table 4
EVALUATION OF DECOMPOSITION TECHNIQUES

Parameter	Weighting Factor	Thermal Bed	Nonspontaneous Catalyst Bed	Spontaneous Catalyst Bed
Volume	20	10	15	20
Start capability	20	10	15	20
Capability of running with $N_2H_4/H_2O/N_2H_5NO_3$ propellant mixtures	15	7	10	15
Initial cost	15	15	12	10
Refurbishment cost per start	15	8	8	15
Major refurbishment cost	10	10	8	6
Packaging flexibility	10	6	8	10
Environmental capability for sustaining repeated vibration loads	10	10	7	7
Total	115	76	83	103

2.3.3 Catalyst Selection

Catalysts other than Shell 405 are available for the decomposition of hydrazine-based propellants. Other catalysts available in the industry are shown in Table 5. These catalysts have been evaluated for use in the jet engine starter gas generator.

Shell 405 is the catalyst which is currently used in all major space programs involving monopropellant hydrazine thrusters. It is the only spontaneous catalyst which has flight experience and has been extensively characterized and developed for monopropellant applications. The catalyst uses iridium metal deposited on a Reynolds alumina (RA-1) alumina substrate. Because of the high cost of iridium metals and the processing costs, the catalyst is relatively expensive. It should be remembered, however, that for the jet engine starter, the catalyst can be reclaimed after use so that its effective cost is substantially reduced.

The aforementioned catalysts have been evaluated quantitatively for application for the jet engine starter program. This evaluation, presented in Table 6, considered spontaneity, strength, susceptibility to oxidation and atmospheric contamination, cost, availability, catalyst stability, packaging flexibility within the thrust chamber, refurbishment costs, vibrational load capability, and catalyst life in terms of total burn time and number of starts capability. Based upon these considerations, the study indicates that the mixed catalyst bed approach represents the optimum approach for the jet engine starter gas generator. It satisfies all performance constraints while still providing an overall bed of high activity in a cost-effective manner. The selected catalyst bed is one containing Shell 405 in the inner bed next to the injector and LCH-202 in the remainder of the bed.

2.3.4 Gas Generator Packaging

Two packaging approaches are used at RRC in gas generator design. These two design approaches shown schematically in Figure 11 consist of axial flow and radial flow techniques. The axial flow packaging technique is normally employed in the lower thrust level regimes (i.e., less than 50- to 100-lbf thrust level), and radial flow geometries are employed above this level.

The radial flow geometry was initially selected for the Phase I flight concept design configuration as shown in RRC drawing SK 5585 (Figure 12, paragraph 2.4). However, detailed analysis during Phase II prototype gas generator design activities indicated that the space available for packaging the gas generator in the starter breech base resulted in unforeseen complexity in the design of the catalyst bed containment structure to accommodate thermal growth of the catalyst during generator operation.

A review of the alternates available resulted in the final design approach that utilizes eight small axial flow gas generator elements arranged in parallel, as shown in Figure 43 of paragraph 3.4.

2.4 FLIGHT CONCEPT

The design of the Phase I flight concept version of the hydrazine-fueled starter is discussed below.

Table 5
GENERAL CHARACTERISTICS OF CANDIDATE
JET ENGINE STARTER CATALYSTS

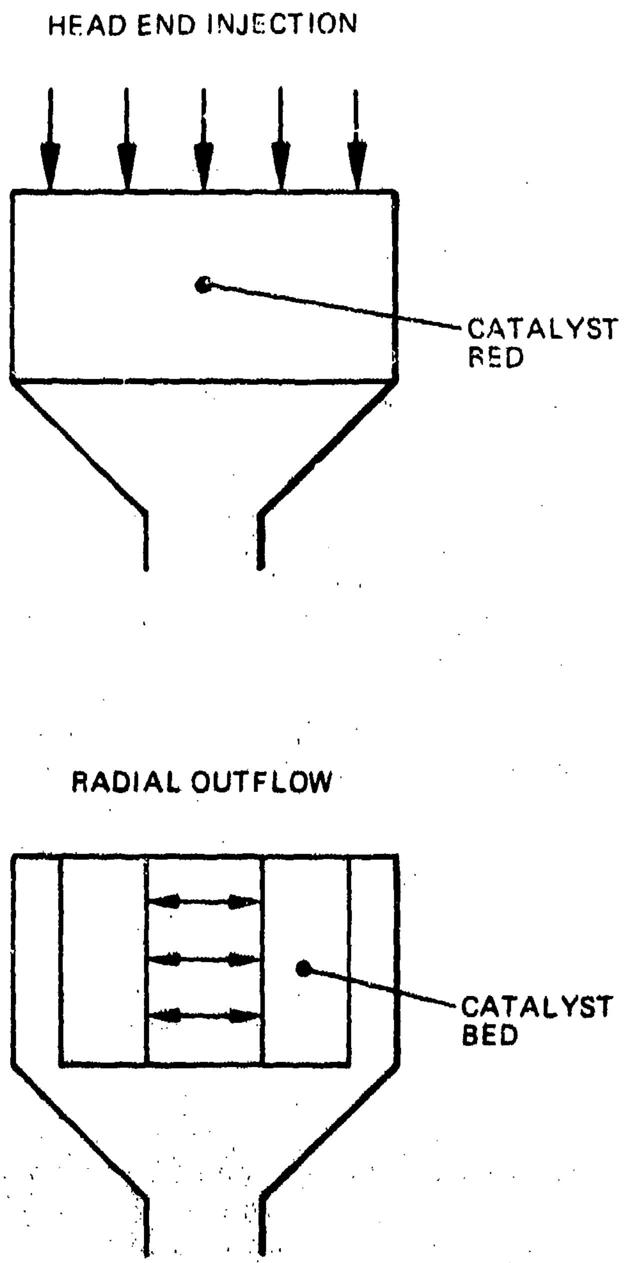
Catalyst	Cost per lbm	Spontaneity	Relative Activity
Shell 405	$4,000	Spontaneous at ambient temperature or below	High
Shell X-B	$300	Low at ambient temperature	Low
Shell X-C	$600	Spontaneous at ambient temperature	Med
Shell X-4	$600	Spontaneous at ambient temperature	Med/High
Shell experimental	~$500	Spontaneous at ambient temperature	High
ESSO 500	~$300	Spontaneous at ambient temperature	High
Pioneer	In range of Shell X-series	Low at at ambient temperature	Low
LCH-101	$100	Nonspontaneous at ambient temperature	Low
LCH-202	$450	Nonspontaneous at ambient temperature	–

Table 6

RESULTS OF CATALYST EVALUATION FOR JET ENGINE STARTER

Parameter	Weighting Factor	Shell 405	Shell X-B	Shell X-C	Shell X-4	Shell Experimental	Pioneer	ESSO 500	Shell 405/ LCH 101	Shell 405/ LCH 202
Spontaneity	20	20	5	10	12	15	5	15	20	20
Susceptibility to oxidation and atmospheric contamination	20	10	5	5	5	10	15	5	15	17
Initial cost	15	5	14	12	12	13	13	13	9	9
High temperature stability	15	12	5	5	5	9	5	15	11	12
Refurbishment cost	15	5	14	12	12	13	13	13	10	10
Environmental capability	15	15	15	15	15	15	10	5	15	15
Total burn time capability	15	15	5	5	5	8	5	2	10	15
Multiple start capability	15	15	5	5	5	8	3	5	12	15
Packaging flexibility	10	10	10	10	10	10	7	10	10	10
Total	140	107	78	79	81	101	76	83	112	123

GAS GENERATOR CATALYST BED PACKAGING APPROACHES



2.4.1 Preliminary Design – Flight Concept Hydrazine Starter

The preliminary design of the flight concept hydrazine starter is shown in RRC drawing SK 5585 (Figure 12). Major system components include:

a. The main gas generator

b. A 181-in.^{3} fuel cartridge

c. A hydrazine-fueled pressurization subsystem that is used to pressurize the fuel cartridge and expel the fuel during starter operation.

In this system concept, the gas generator would be permanently installed in the breech base of the starter. The fuel cartridge and the pressurization subsystem would fit in the removable breech cap. The fuel cartridge would be expendable and replaced after each start cycle. The pressurization subsystem would be partially expendable requiring the replacement of a fuel/pressurant/explosive valve module after each start cycle.

The main gas generator was assumed to be capable of operating through a minimum of 400 full power starter operating cycles without maintenance. The gas generator was a radial flow device using Shell 405 spontaneous catalyst in the inner bed and LCH-202 catalyst in the outer bed. Fuel from the fuel cartridge would be injected uniformly over the innermost porous surface of the inner bed catalyst retainer, and the hot gas would exit uniformly and radially through a partially open outer catalyst bed retention cylinder. The breech base would function as the pressure vessel to contain the hydrazine exhaust gas. The turbine hot gas nozzles in the starter would provide the necessary flow limiting control.

The fuel cartridge would contain 181-in.^{3} of a hydrazine-based fuel mix designated as TSF-1 (turbine starter fuel-1). It was estimated that this quantity of fuel would be sufficient to duplicate the energy content of the MXU4A/A solid propellant fuel cartridge. The fuel would be contained in a elastomeric bladder, and the bladder would be packaged in a lightweight plastic shell for protection during handling. The fuel cartridge would interface with the fuel inlet stem on the main gas generator through an O-ring sealed fitting. The interface fitting on the fuel cartridge would include a burst disc for fuel retention during handling and storage. The burst disc would rupture during breech pressurization allowing fuel flow to the main gas generator. Fuel containment with the bladder would assure that the starter would operate in any attitude.

The pressurization subsystem is shown schematically in Figure 13. A total of 8.8 cubic inches of high pressure nitrogen gas is contained in a coiled tube bundle and retained by a normally closed explosive valve that interfaces physically with the electrical connector in the breech cap that is normally used to fire the squib in the solid propellant cartridge. When the starter is operated, the explosive valve is fired, releasing the high pressure nitrogen through a pressure regulator where it is then used to pressurize and expel 11 cubic inches of the hydrazine-based TSF-1 fuel mixture through a small catalytic reactor. The fuel mix is also stored in a coiled tube bundle; this technique will assure that the pressurization subsystem will operate in any physical attitude. The pressure-regulated exhaust products from the small catalytic pressurization reactor pressurize the breech, expelling the fuel from the fuel cartridge into the main gas generator.

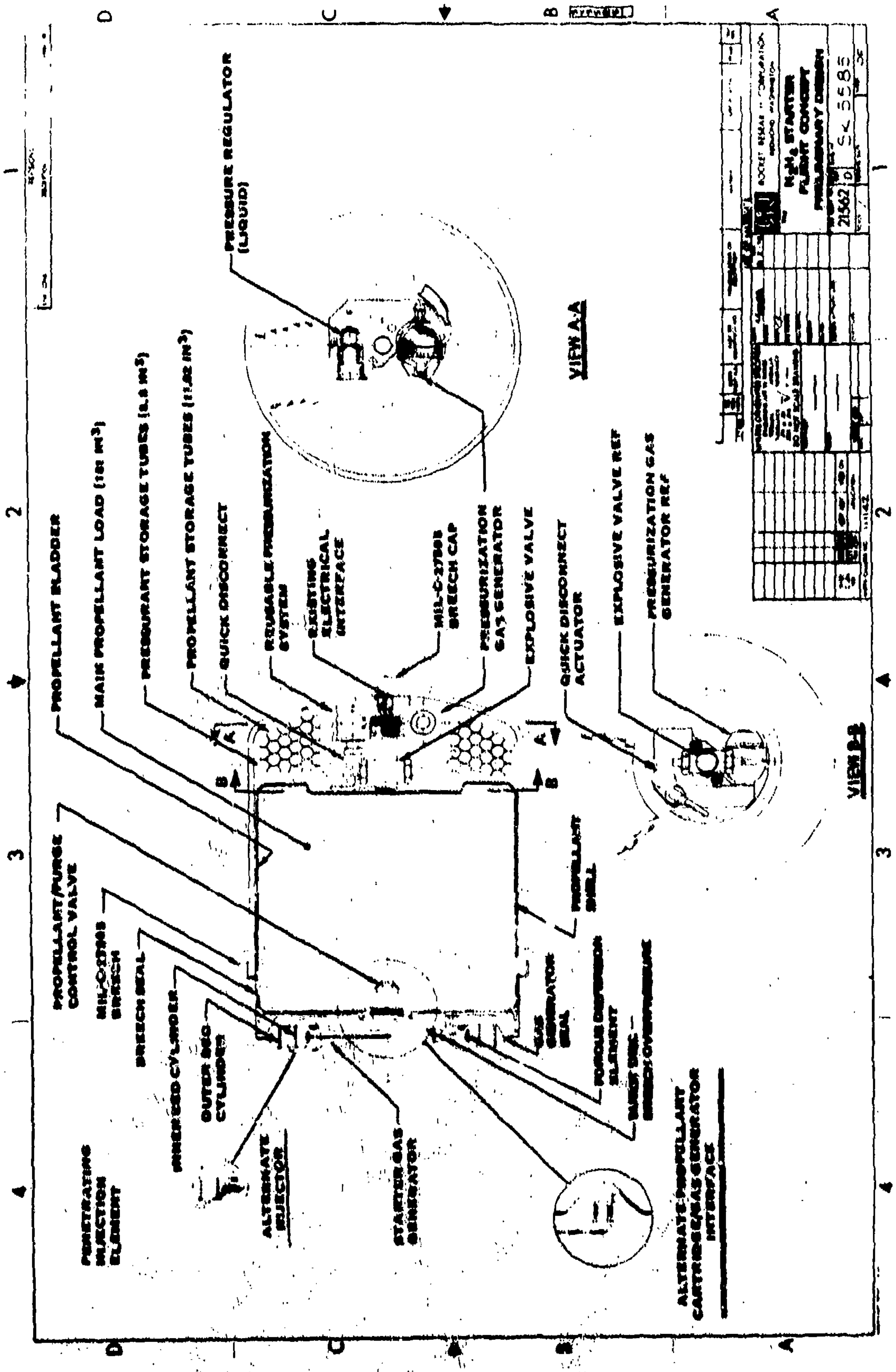
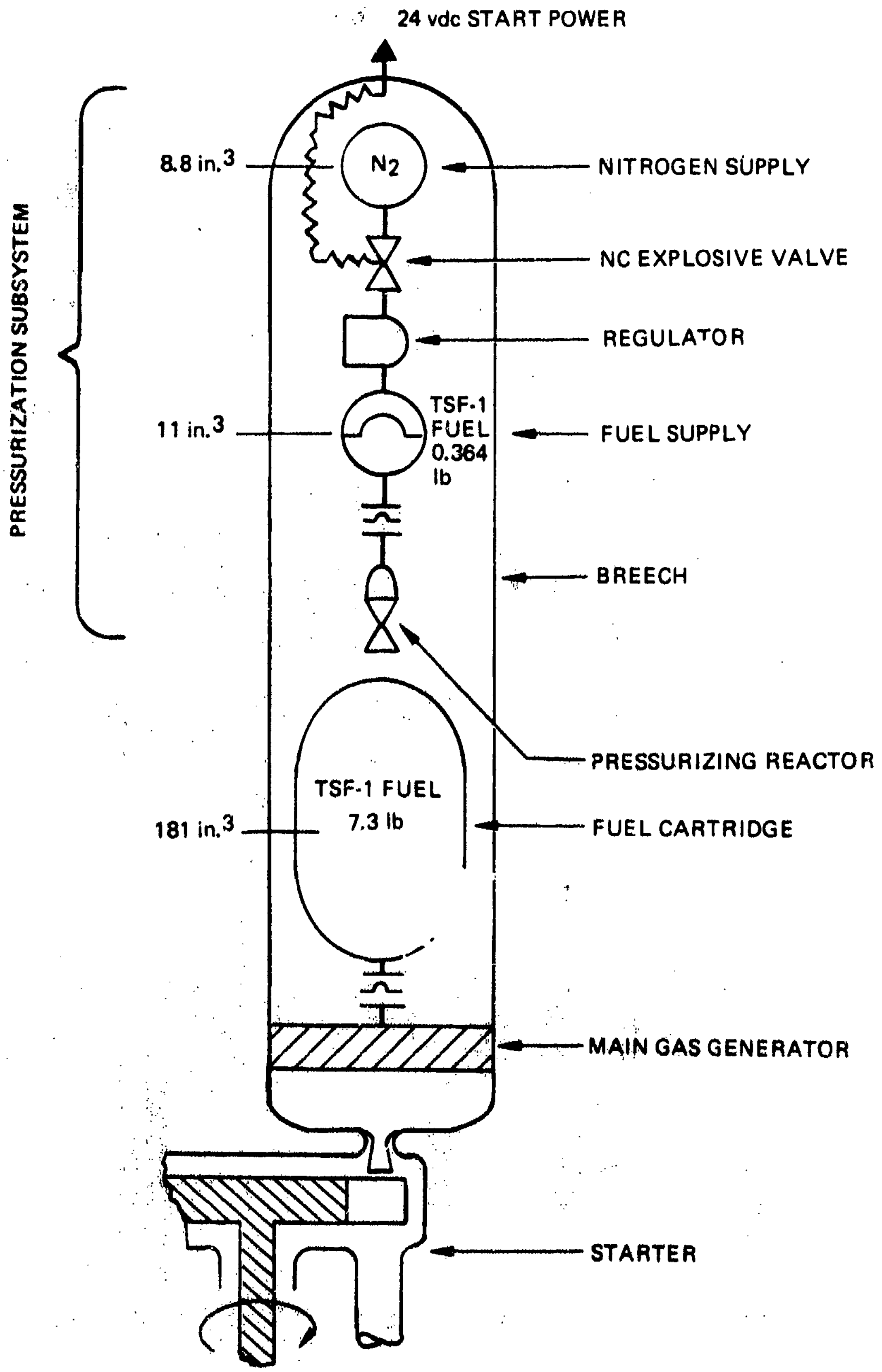

PRESSURE REGULATOR (LIQUID)
VIEW A-A
PROPELLANT BLADDER
MAIN PROPELLANT LOAD
PRESSURANT STORAGE TUBES
PROPELLANT STORAGE TUBES
QUICK DISCONNECT
REUSABLE PRESSURIZATION SYSTEM
EXISTING ELECTRICAL INTERFACE
BREECH CAP
PRESSURIZATION GAS GENERATOR
EXPLOSIVE VALVE
QUICK DISCONNECT ACTUATOR
EXPLOSIVE VALVE REF
PRESSURIZATION GAS GENERATOR REF
VIEW B-B
PROPELLANT SHELL
PROPELLANT/PURGE CONTROL VALVE
BREECH SEAL
INNER FEED CYLINDER
OUTER FEED CYLINDER
PENETRATING INJECTION ELEMENT
ALTERNATE INJECTOR
STARTER GAS GENERATOR
GAS GENERATOR SEAL
POROUS DISPERSION ELEMENT
ALTERNATE PROPELLANT CARTRIDGE/GAS GENERATOR INTERFACE
ROCKET RESEARCH CORPORATION
STARTER
FLIGHT CONCEPT
PRELIMINARY DESIGN
21562
SK 5585

Figure 12

BREECH PRESSURIZATION CONCEPT



When the fuel supply in the fuel cartridge is depleted, the fuel cartridge to gas generator interface fitting is designed to shuttle and allow the breech pressurant to vent through the main gas generator allowing post-starter operation access to the breech area for the replacement of expendables.

2.4.2 Predicted Operating Characteristics of the Hydrazine-Fueled Starter

Considerable insight into the energy available for cartridge starter operation was obtained by reviewing the military specification for the MXU4A/A solid propellant cartridge (MIL-C-27505B) and a literature survey of papers published by propellant suppliers. The military specification established operating pressure limits, minimum pressure time integrals, and burn time requirements for the solid propellant cartridge. The literature review defined typical solid propellant exhaust gas properties including theoretical gas temperature, molecular weight, composition and γ (the ratio of Cp/Cv).

This information was used in conjunction with the generalized equations available for impulse turbine performance analysis and the known thermochemical performance characteristics for the hydrazine-based fuel blends selected for the starter program to establish the operating pressure run time and quantities of expendables required for the flight concept preliminary design.

The results of the analysis are summarized in Figure 14 for soak temperatures of -65, ambient, and +160°F. The quantities of expendables shown will theoretically provide hydrazine-fueled starter operation equivalent to that obtained with the MXU4A/A solid propellant cartridge.

2.5 PHASE II PROGRAM/TEST PLAN

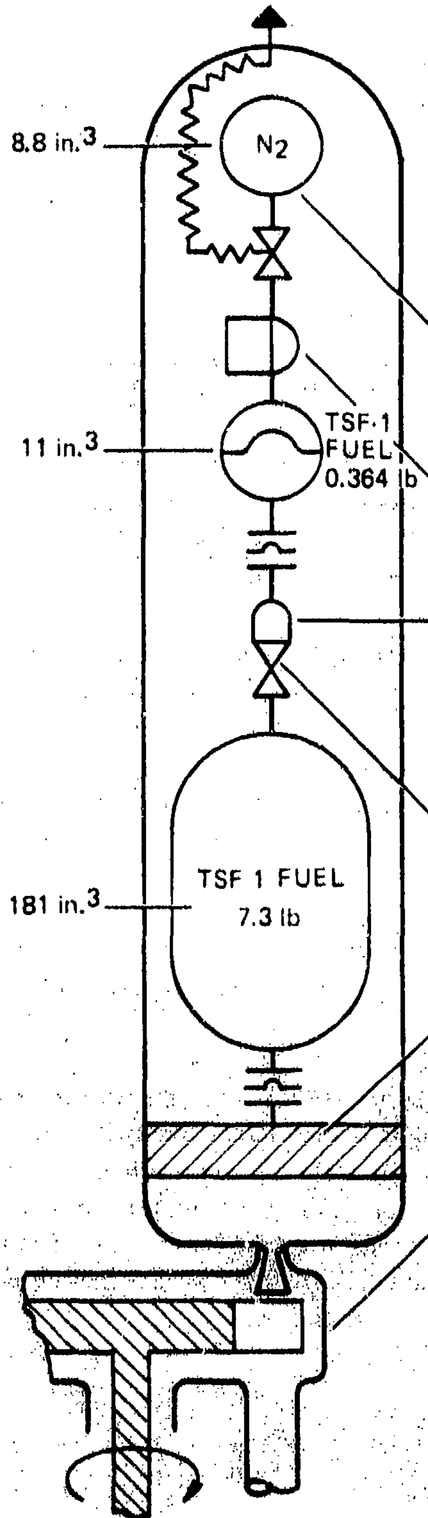
The Phase II program plan is summarized in Figure 15. The plan included five distinct tasks as follows.

The initial task involved the design and fabrication of the prototype flight concept gas generator followed by component level testing of the unit, in conjunction with the breadboard fuel supply system, to verify the adequacy of the gas generator operating characteristics at -65, ambient, and +160°F operating conditions.

Task II included the installation of the universal starter test stand and the conduct of multiple starter test firings in the "cartridge mode," at -65, ambient, and +160°F soak conditions to determine the performance characteristics of the cartridge starter.

The prototype flight concept gas generator would then be adapted to the cartridge starter, and the starter performance would be monitored during Task III. The performance of the hydrazine-fueled starter would be compared to the "cartridge mode" results of Task II, verifying the adequacy of the hydrazine starter concept and establishing fuel consumption per start cycle requirements at -65, ambient, and +160°F operating conditions. Task III testing would then continue until a minimum of 20 full power starter operating cycles had been accumulated to demonstrate a limited life capability of at least 20 starts on the prototype flight concept gas generator.

PHASE I PRELIMINARY SYSTEM SIZING ANALYSIS SUMMARY



-65	Ambient	+160
3,000 psia 1,200 psia	4,780 psia 1,690 psia	5,850 psia 1,950 psia
	1,135 psia	
1,030 psia x = 0.6 1,861°R $\dot{\omega}$ = 0.0222 lb/sec	1,030 psia x = 0.6 2,036°R $\dot{\omega}$ = 0.0212 lb/sec	1,030 psia x = 0.6 2,144°R $\dot{\omega}$ = 0.207 lb/sec
1,030 psia 865°R	1,030 psia 873°R	1,030 psia 881°R
931 psia x = 0.4 2,054°R $\dot{\omega}$ = 0.49 lb/sec	935 psia x = 0.4 2,227°R $\dot{\omega}$ = 0.47 lb/sec	939 psia x = 0.4 2,331°R ω = 0.46 lb/sec
18 psia 932°R	18 psia 1,038°R	18 psia 1,085°R
Run Time 14.9 sec	Run Time 15.5 sec	Run Time 15.9 sec

Figure 14

CRITICAL PATH ANALYSIS SUMMARY – PHASE II TEST PROGRAM

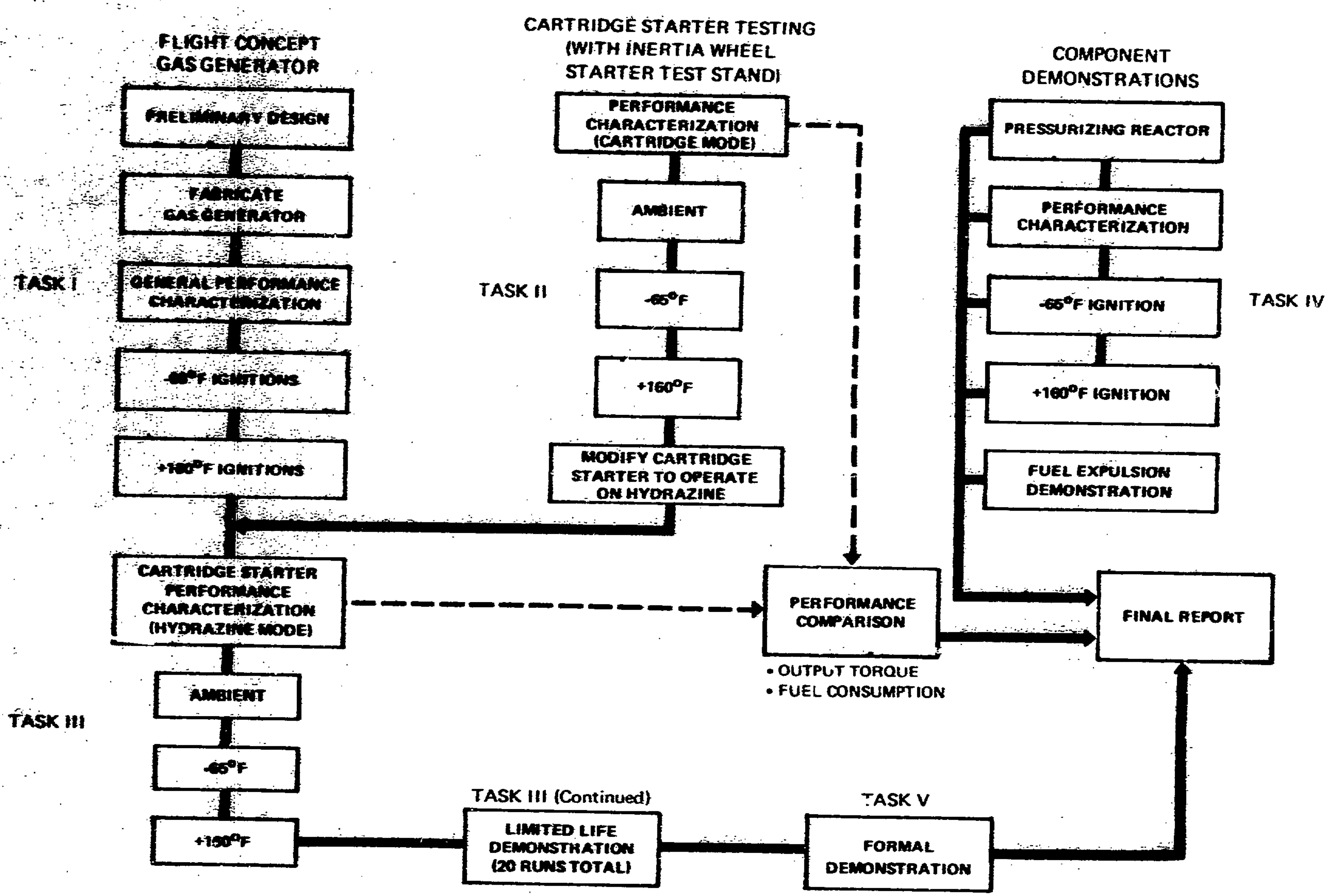


Figure 15

During Task IV, component level testing would be conducted to evaluate the basic adequacy of the flight concept pressurization subsystem and the fuel cartridge. Funding limitations would limit these tests to pressurizing reactor performance characterization using the breadboard fuel supply system in place of the flight concept coiled tube bundle fuel supply, and fuel expulsion tests using a representative elastomeric bladder and cold nitrogen gas to expel water from a test device to verify acceptable fuel expulsion efficiency with the proposed fuel cartridge system geometry.

The hydrazine-fueled starter would be operated in conjunction with the breadboard fuel supply system during a formal demonstration as Task V. The contracting agency and other interested user organizations would witness this demonstration, which would be combined with a formal presentation of the Phase I/Phase II program results.

SECTION III
PHASE II – EXPERIMENTAL TESTING AND DEVELOPMENT

This portion of the report describes the test hardware and the experimental test results associated with the feasibility demonstration of the hydrazine fueled starter concept.

3.1 BREADBOARD FUEL SUPPLY SYSTEM

The hydrazine-fueled starter feasibility test program did not require the design and fabrication of the complete "in-breech" hydrazine fueled gas generating system. A prototype, flight concept gas generator was fabricated and installed in the breech base of the starter, but the flight concept type fuel cartridge and its pressurization subsystem were not fabricated due to the feasibility nature of the program. Fuel supply to the starter was accomplished with a laboratory type, pressure-regulated breadboard fuel supply system with a capacity of 2-1/2 gallons.

The breadboard fuel supply system is shown schematically in Figure 16. The system consists of a 2-1/2 gallon fuel tank, control valves, flowmeters, and instrumentation to monitor fuel pressure and fuel temperature. The breadboard fuel supply system was mounted in a 25-ft^3 environmental test chamber to allow temperature conditioning of the fuel supply, prior to starter operation.

A sightglass was installed in parallel with the 2-1/2-gallon fuel tank. The calibrated sightglass was used to monitor the total quantity of fuel consumed per start cycle by recording the pretest and post-test liquid levels in the unpressurized tank. Instantaneous fuel rates were monitored with two turbine type flowmeters.

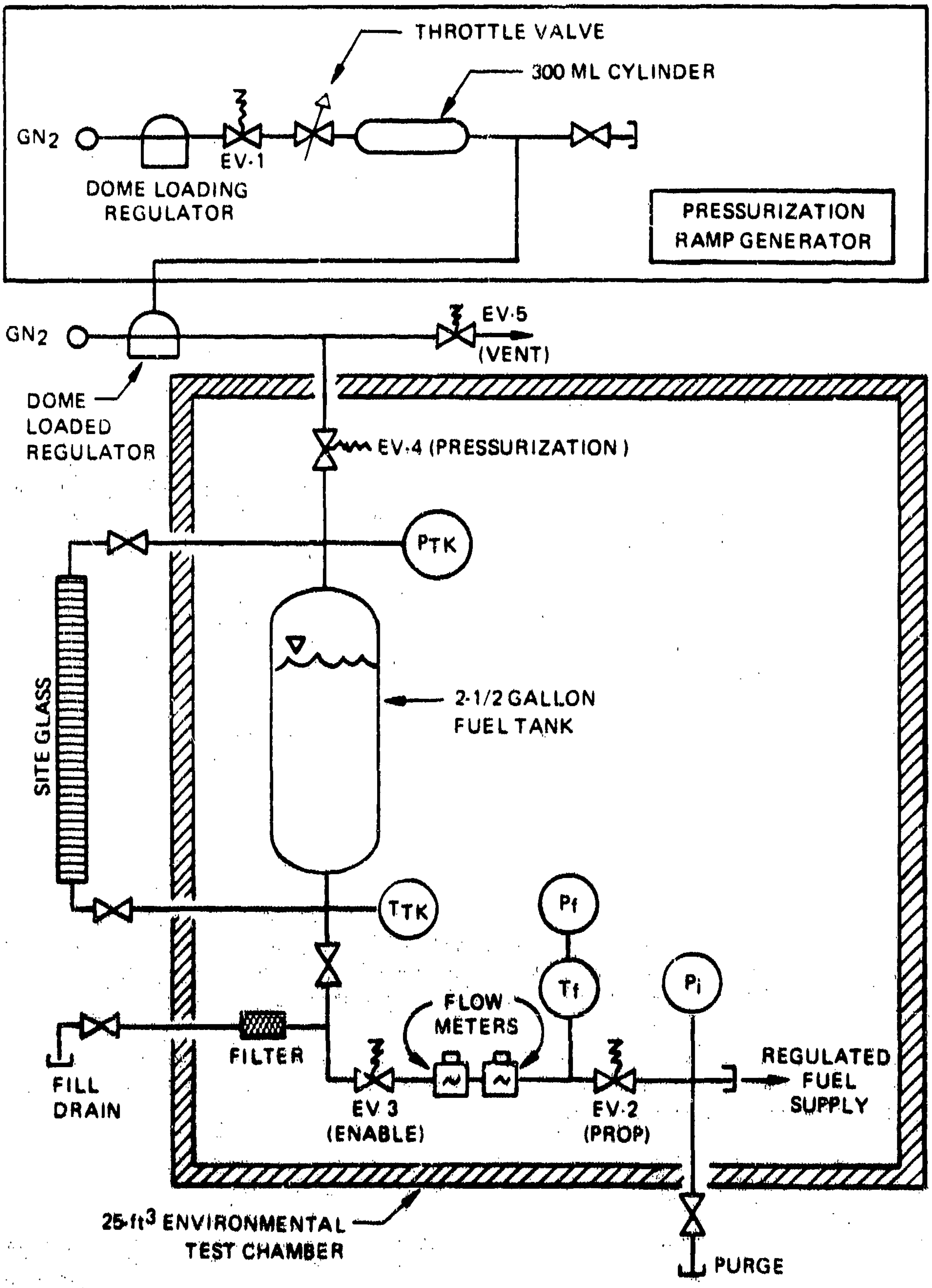
The breadboard fuel supply system was pressurized with high pressure gaseous nitrogen through a dome-loaded pressure regulator.

3.1.1 Pressurization Ramp Generator

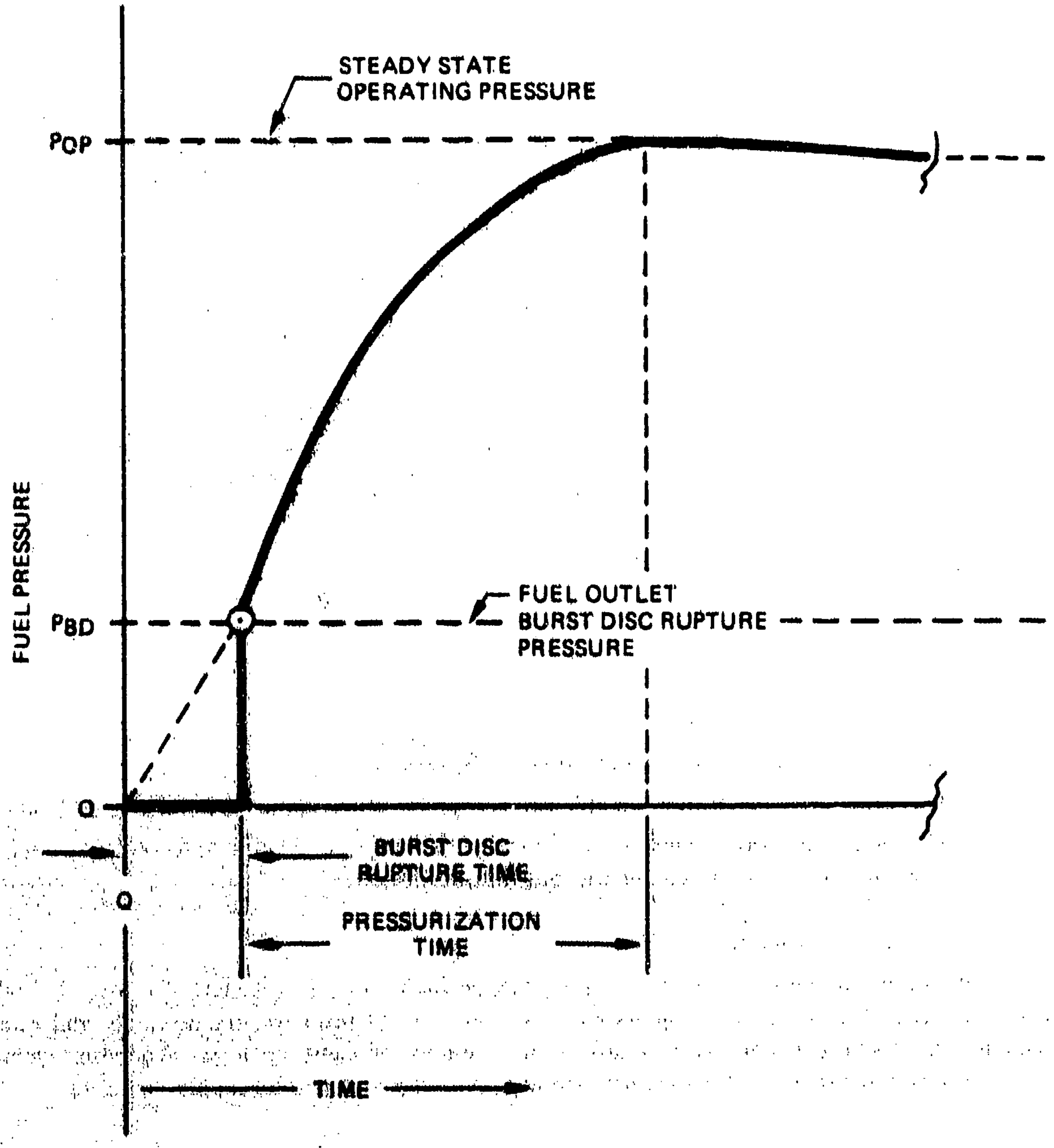
Figure 17 depicts the fuel pressure versus time characteristics of the flight concept hydrazine starter. At time zero, the pressurization subsystem would be initiated, and the breech pressure would increase to the valve P_{BD} which would rupture the fuel containment burst disc in the fuel cartridge allowing initial fuel flow to the main gas generator. The breech pressure and the pressure of the fuel supplied to the main gas generator would continue to increase to the equilibrium value during the time interval denoted in Figure 17 as the pressurization time.

The fuel outlet burst disc rupture pressure (P_{BD}), the steady-state operating pressure level (P_{OP}), and the pressurization time interval are system design variables that can be varied consistent with the performance requirements of the starter.

BREADBOARD FUEL SUPPLY SUBSYSTEM



PRESSURIZATION RAMP GENERATOR CONCEPT
FUEL PRESSURE VS TIME CHARACTERISTICS



The breadboard fuel system utilized a pressurization ramp generator to simulate burst disc rupture and pressurization rate control in a meaningful manner. This system functions as follows:

a. Prior to firing the gas generator, the dome loading regulator was set to a predetermined pressure P_{BD}, typically in the 20- to 100-psig range. EV-1 was opened and the 2-1/2 gallon tank pressurized to the P_{BD} value.

b. EV-1 was then closed, and the dome loading regulator was then set to the desired steady-state fuel pressure (P_{REG}).

c. The gas generator was then fired by simultaneously opening the main propellant control valve EV-2 and the pressurization control valve EV-1. The time required to pressurize the 2-1/2-gallon fuel tank from the initial pressure P_{BD} to the desired steady-state fuel pressure P_{OP} could be varied (and controlled) by presetting the throttle valve in the pressurization ramp generator which in effect controlled the time required to charge the 300-ml cylinder in the ramp generator, providing a controlled pressure versus time input to the dome-loaded regulator which in turn was used to establish the pressure in the 2-1/2-gallon fuel tank.

Figures 18 and 19 are photographs of the breadboard fuel supply system and the 25-ft^3 environmental chamber.

3.2 SUBSCALE TESTING

Initial Phase II testing was conducted with a subscale gas generator as discussed in the following subsections. The primary objective of the subscale gas generator test program was to verify the adequacy of the proposed design prior to committing to the fabrication of the flight concept (8-cup) gas generator.

Test objectives included verification that:

a. The catalyst bed design was adequate.
   1. Proper bed length
   2. Proper bed loading
   3. Mixed catalyst bed approach viable

b. Reliable ignition could be obtained at -65°F soak conditions.

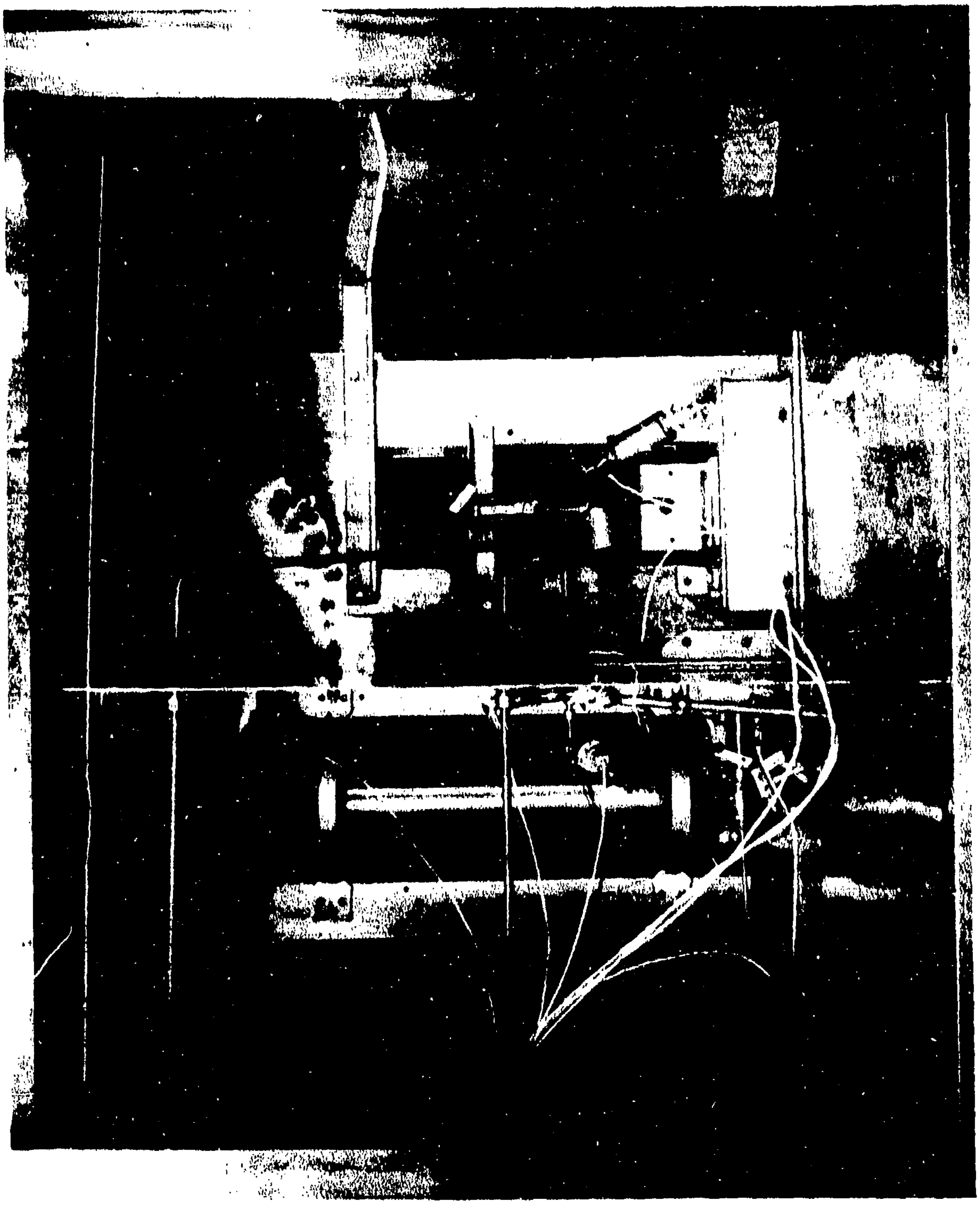
c. Gas generator operation was stable and acceptable with candidate ternary fuel blends.

d. Gas generator was capable of successfully meeting the 20 full power starter operating cycle limited life requirement without refurbishment.

3.2.1 Subscale Gas Generator

Figure 20 is a photograph of the eight-cup prototype flight concept gas generator assembly which was taken after the major components were oven brazed but prior to final assembly and catalyst loading. The flight concept gas generator is an assembly of eight small gas generating elements (cups) arranged in parallel and fed from a common, centrally located fuel supply manifold.

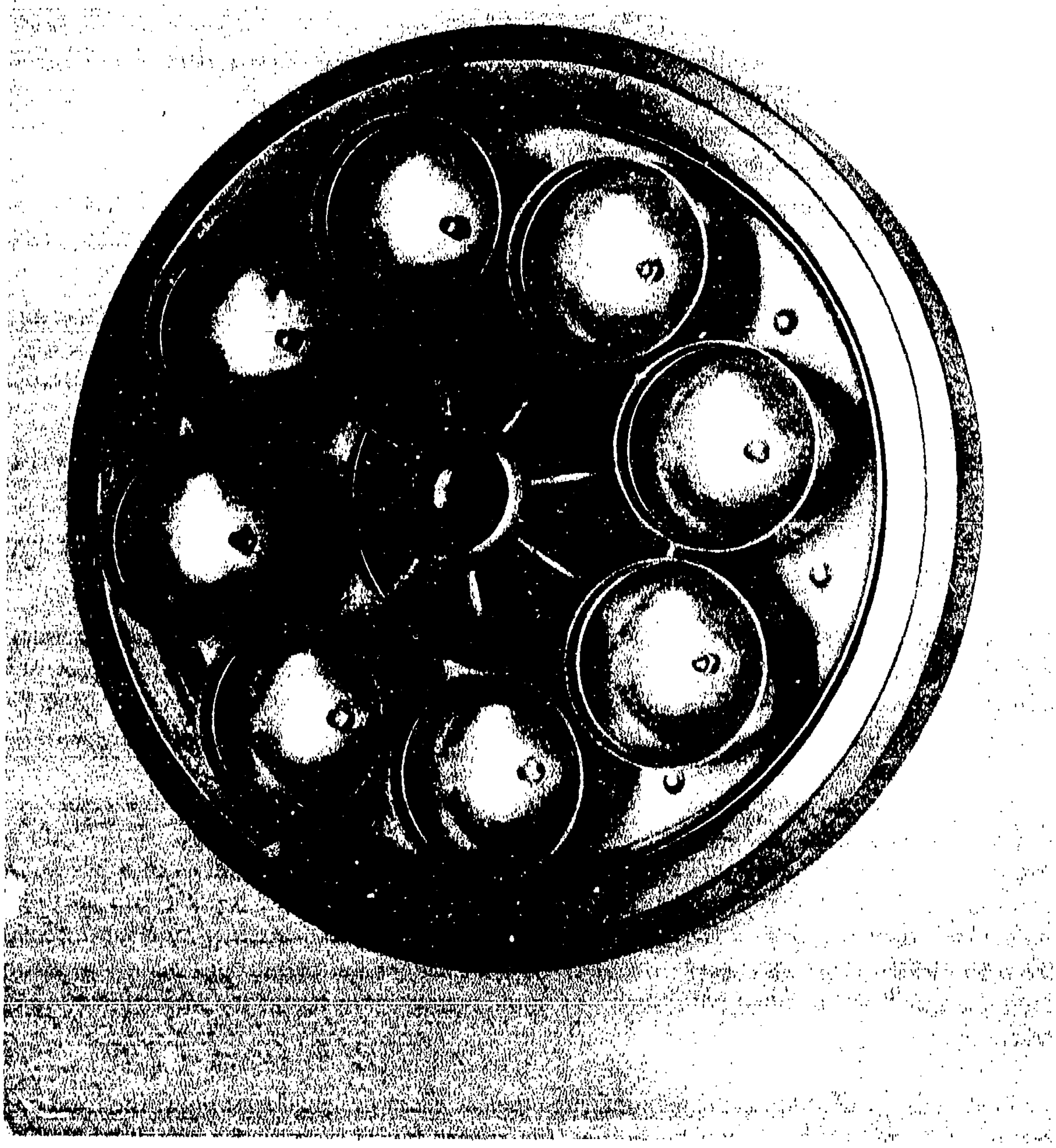
BREADBOARD FUEL SUPPLY SYSTEM



BREADBOARD FUEL SUPPLY SYSTEM

Figure 19

FLIGHT TYPE GAS GENERATOR (8 CUP) AFTER OVEN BRAZING



Prior to committing to the fabrication of the eight-cup prototype flight concept gas generator, an extensive test program was conducted with a subscale gas generator which consisted of one cup, similar in geometry to those proposed for the flight concept unit.

Subscale testing with the single-cup gas generating element allowed rapid and cost-effective design modifications, reduced the quantity of fuel required to evaluate the operating characteristics, and resulted in meaningful and reliable test results that were not subjected to scaling effects.

Figure 21 is a sketch of the subscale gas generator that was utilized to evaluate the adequacy of the proposed cup type gas generating elements for the flight concept gas generator. The major features of the subscale gas generator are as follows.

3.2.1.1 Single-Cup Gas Generating Element

The cup assembly includes the cup, fuel injector, catalyst, bed screen, bedplate, and the bedplate retainer. The geometry of the single-cup gas generating element was identical to that proposed for the flight concept gas generator application with two minor exceptions:

a. The overall length of the cup was slightly longer. The cup length downstream of the bedplate was extended slightly to accommodate multiple rework operations that would be required if the catalyst bed composition or catalyst bed geometry had to be changed during the subscale evaluation testing.

b. The fuel inlet on the subscale cup was located on the axis of symmetry of the cup for convenience of adapting a fuel control valve to the subscale gas generator.

   The flight concept gas generating elements (cups) have their fuel inlet fittings located at right angles to the axis of symmetry to the cup.

The cup, fuel injector, bedplate, and bedplate retaining ring were fabricated from 347 stainless steel. The injector was oven brazed to the cup with Palniro I braze metal. After loading a predetermined quantity of catalyst into the cup, the bedplate was installed and held in place by the bedplate retaining ring. The retaining ring to cup joint was then sealed by a continuous melt-down TIG weld.

For the initial subscale gas generator test series, the catalyst bed consisted of 6.0 grams of 25- to 30-mesh granular Shell 405 spontaneous catalyst loaded into that portion of the catalyst bed immediately adjacent to the injector. Additionally, approximately 8.0 grams of a 14- to 18-mesh nonspontaneous catalyst designated as LCH-202 were loaded into the downstream portion of the catalyst bed. The 405 and LCH-202 catalysts were isolated from each other by means of a 50-mesh screen fabricated from Haynes 25 material. In the final version of the subscale gas generator, the entire catalyst bed was filled with Shell 405 spontaneous catalyst and the intermediate bed screen was eliminated.

It should be noted that the gas generating cup element is not designed to support the total operating pressure differential (P_{gas} - $P_{atmosphere}$). The starter breech acts as the structural element that carries the total operating pressure differential. The individual single cup gas generating elements

SUBSCALE GAS GENERATOR DETAIL

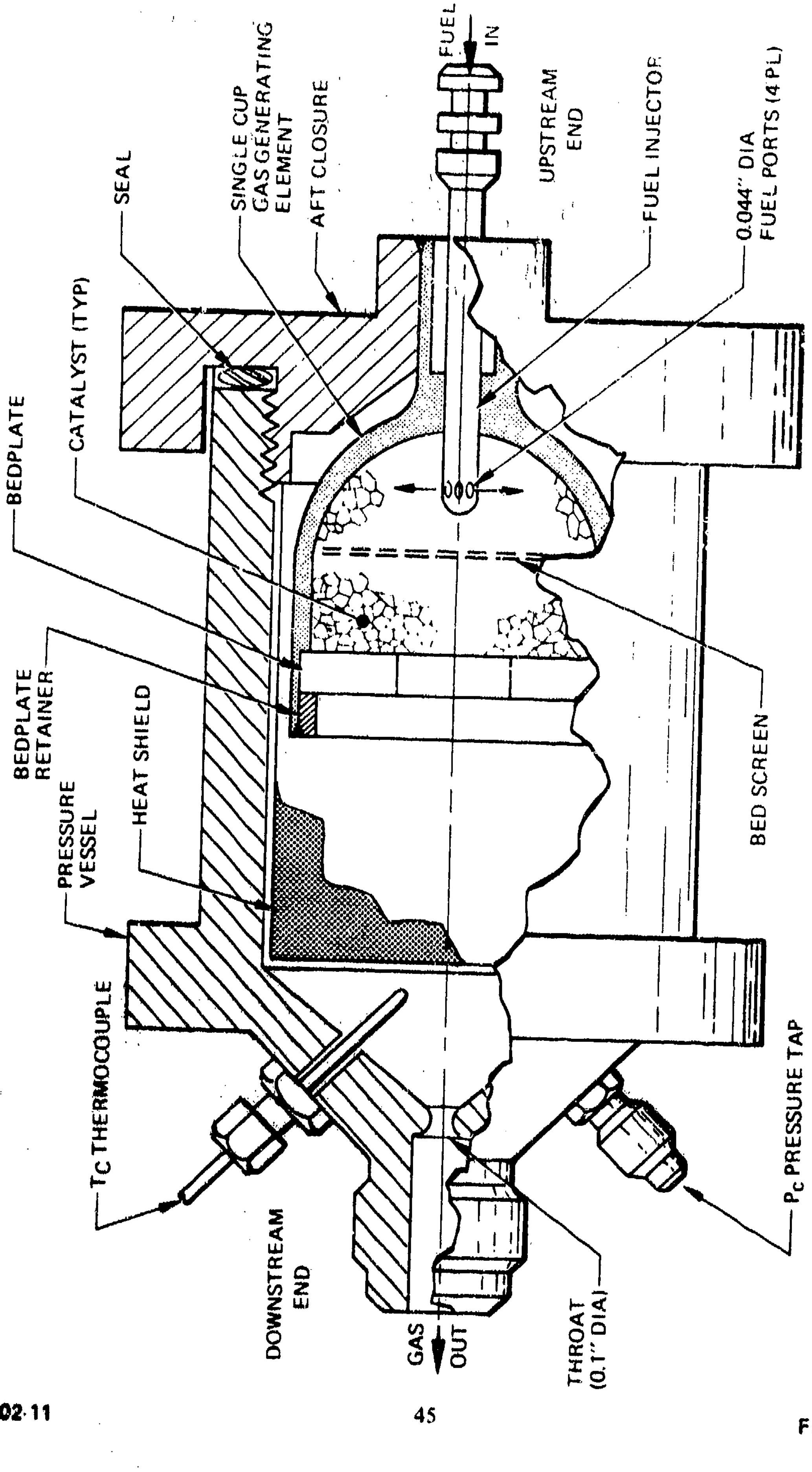


Figure 21

need only have sufficient strength to support the catalyst bed/bedplate pressure drop and transient type starting loads that may occur during the initial flow of fuel into the catalyst bed prior to the initial pressurization of the breech base void volume.

3.2.1.2 Subscale Gas Generator Pressure Vessel

The single-cup gas generating element was contained within a pressure vessel as shown in Figure 21. The internal void volume of the pressure vessel was equivalent to 1/8 of the void volume in the starter breech with the flight concept gas generator assembly installed.

The products of decomposition of the hydrazine-based fuel mix left the generator through an AN type fitting at the downstream end. The single-cup gas generating element was backpressured by a 0.1-inch-diameter converging orifice located in the exhaust fitting. Provisions were provided for monitoring the exhaust gas temperature (T_C) and pressure (P_C) immediately upstream of the 0.1-inch-diameter throat restriction. The single-cup gas generating element was welded to the aft closure to facilitate cup removal from the pressure vessel. The aft closure was adapted to the pressure vessel by a screw thread joint which was sealed with an asbestos filled copper crush ring.

A cylindrical heat shield 0.015/0.020 inch thick was installed between the cup and the inner bore of the pressure vessel to reduce the heat loss from the cup and to reduce the heating of the pressure vessel wall.

3.2.1.3 Photographs of the Subscale Gas Generator

Figures 22 through 24 are photographs of the subscale gas generator assembly.

Figure 22 shows the complete assembly. The thermocouple plug shown with the coiled wire is the thermocouple that was used to monitor the temperature of the fuel injector stem. The capped AN fitting centered on the cylindrical portion of the pressure vessel was not used.

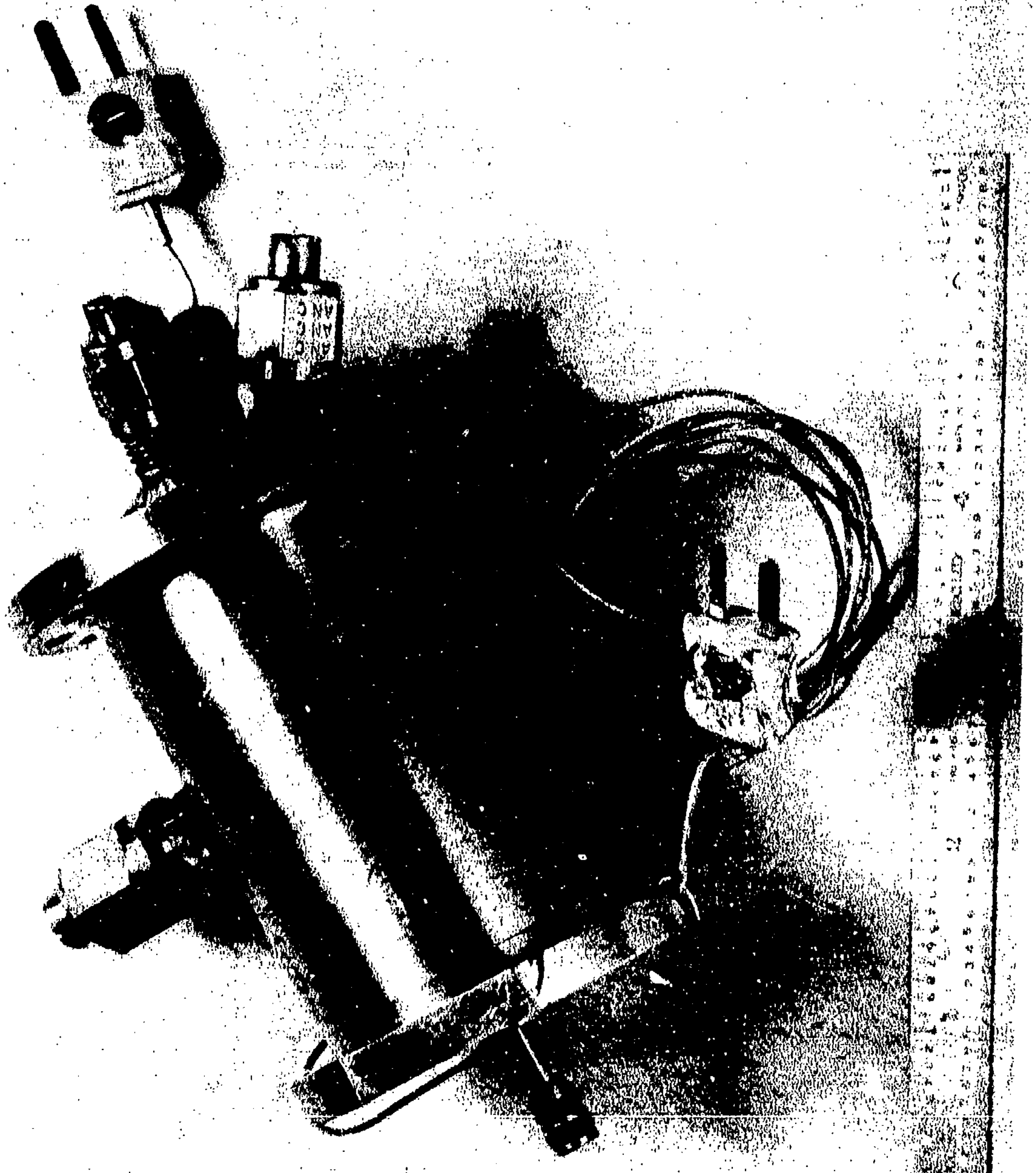
The downstream flange on the pressure vessel is drilled for mounting the assembly to the test fixture. The fuel injector interfaces with the propellant (control) valve through the O-ring sealed stem.

Figure 23 shows the major elements of the subscale gas generator. Left to right are the pressure vessel, cylindrical heat shield, copper crush gasket, and the assembly of the single-cup gas generating element and the aft closure.

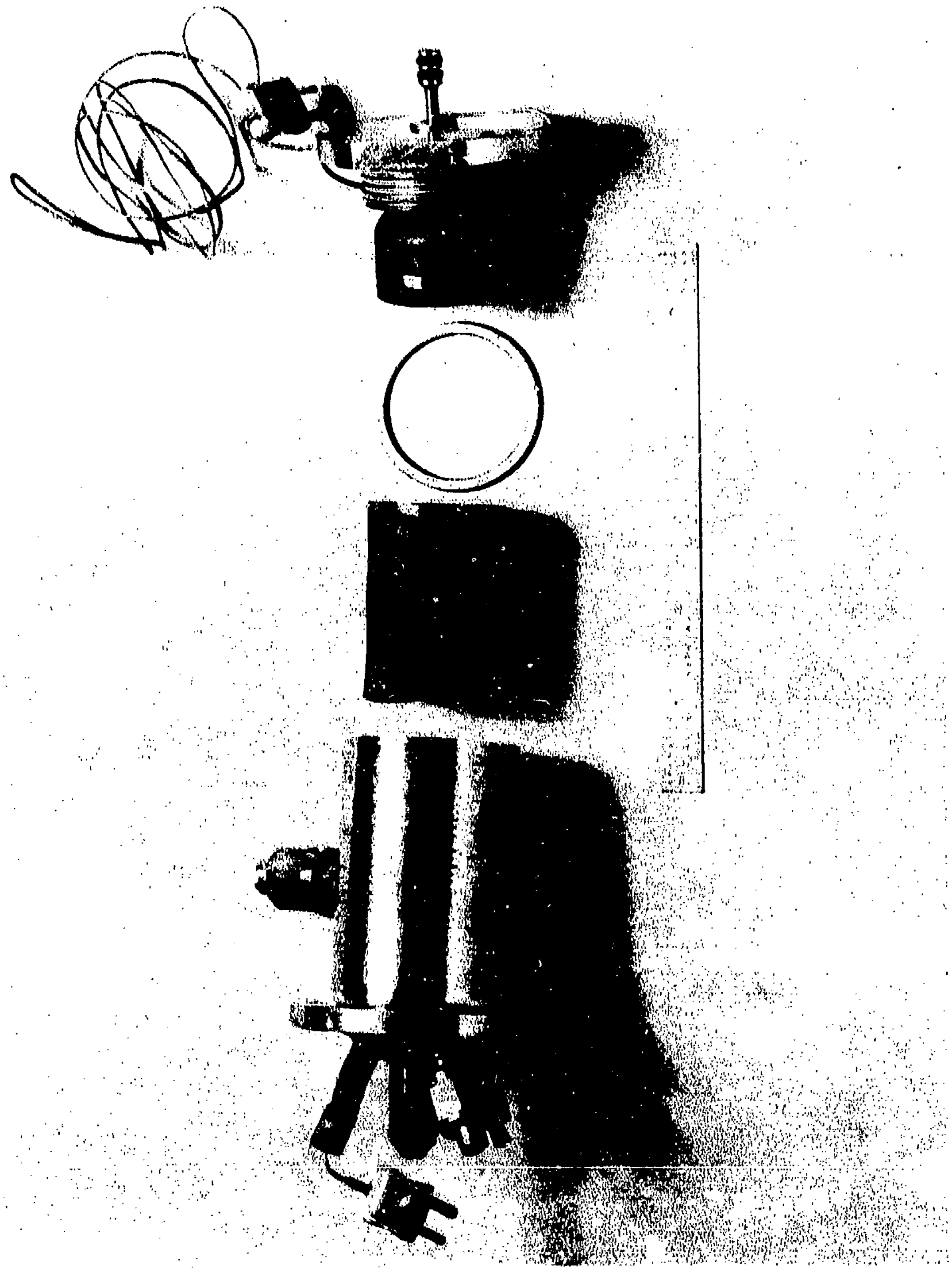
Figure 24 shows the single-cup/aft closure assembly as removed from the subscale gas generator and the component parts of the single-cup gas generating element. Left to right are the bedplate retaining ring, bedplate, bed screen and catalyst, injector screen, cup, and the as-fired single-cup/aft closure assembly.

Twelve slots were machined through the bedplate. The slots provide adequate flow area for the hot gas generated in the catlayst bed. The width of the slots is such that the catalyst granules cannot pass through the slots.

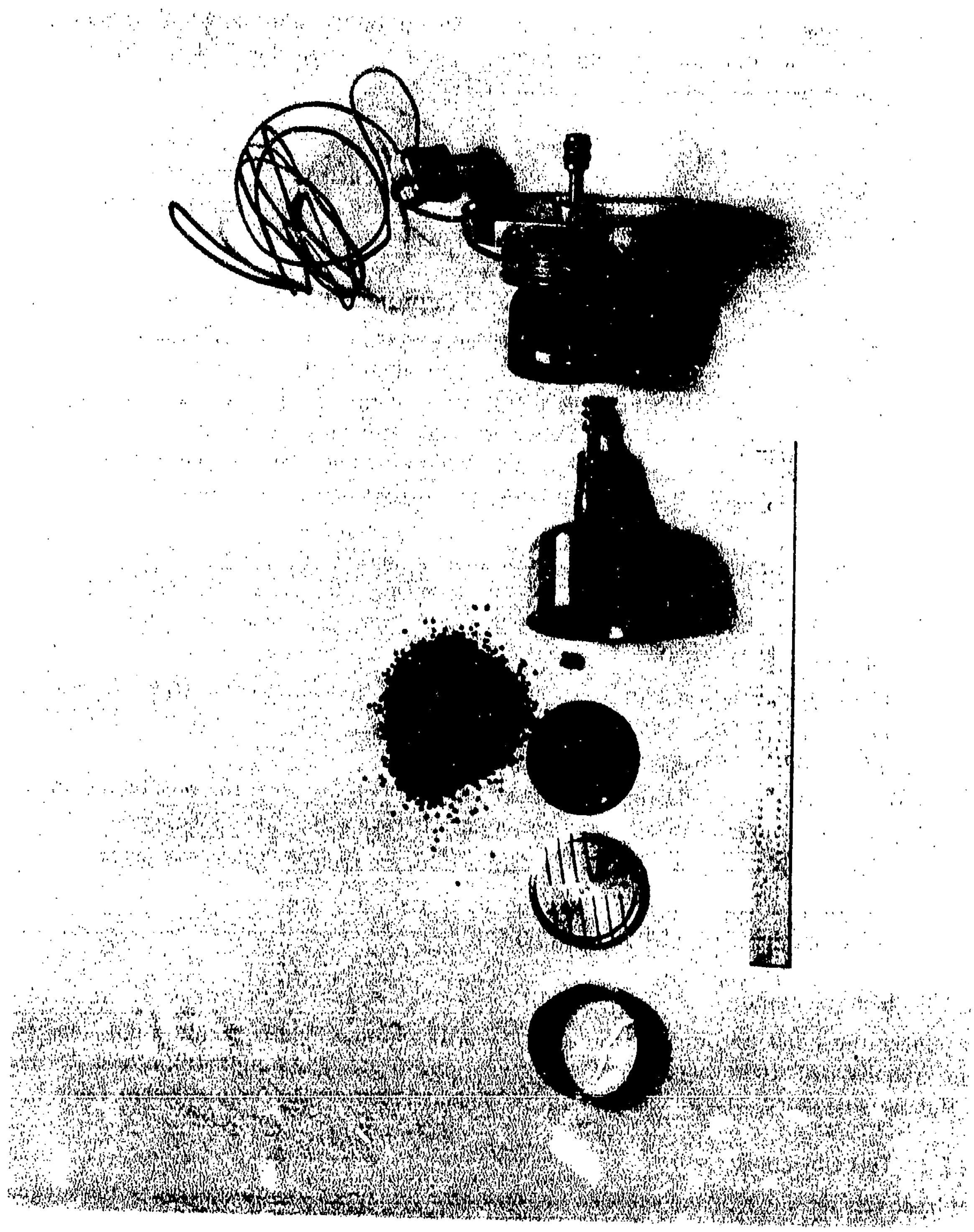
SUBSCALE GAS GENERATOR ASSEMBLY



SUBSCALE GAS GENERATOR COMPONENTS



SUBSCALE GAS GENERATOR DETAILS (SINGLE CUP)



3.2.2 Subscale Gas Generator Test Results

The subscale gas generator was installed in the 25-ft^3 environmental test chamber in conjunction with the breadboard fuel supply subsystem as shown in the photograph of Figure 25. This arrangement allowed simultaneous temperature conditioning of the fuel supply and the gas generator prior to firing the subscale gas generator.

Figure 26 is a sketch of the test installation. The subscale gas generator was oriented with the exhaust nozzle pointed vertically up to simulate the "as installed" attitude of the flight concept gas generator in the breech base of the STU13/A34 cartridge starter. The subscale gas generator and the breadboard fuel supply system were instrumented as shown in Figure 26.

The basic subscale gas generator test procedure used throughout this test series was as follows:

a. With the gas generator installed per Figures 25 and 26, the required soak temperature was established in the environmental test chamber. If the required soak temperature was other than "local ambient," the temperature of the breadboard fuel supply tank (T_{TK}) and the temperature of the subscale gas generator pressure vessel (T_W) were monitored continuously. When T_{TK} and T_W stabilized at the required soak temperature, the system was maintained at the required soak temperature for a minimum of 2 hours prior to firing.

b. At the conclusion of the temperature soak period (if applicable), the fuel tank was pressurized to the desired start pressure (typically 20 to 100 psig), and the dome loading regulator in the pressurization ramp generator was adjusted to the required run pressure (nominally 1,035 psia).

c. The instrumentation recorders were started, and the subscale gas generator was fired by simultaneously opening the propellant valve (EV_2) and the solenoid valve EV_1 in the pressurization ramp generator.

NOTE: The reader should refer to paragraph 3.1 which discusses the breadboard fuel supply subsystem and the pressurization ramp generator to review the "start" sequence.

d. The subscale gas generator firing continued for a nominally 15-second period.

e. At the conclusion of the 15-second burn, the propellant valve (EV_2) was shut and the breadboard fuel supply tank was vented.

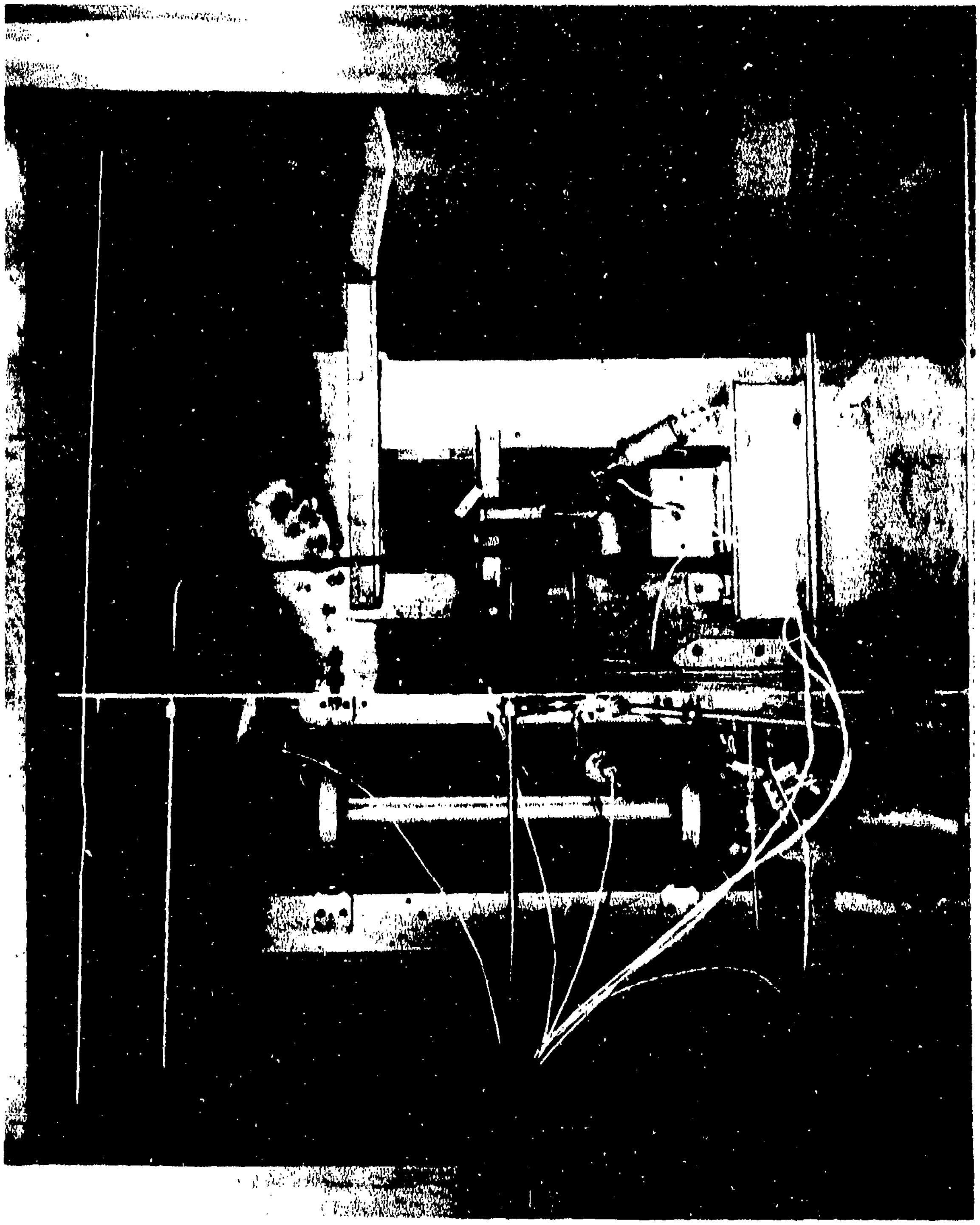
3.2.2.1 Instrumentation

All temperatures and pressures were monitored with chromel-alumel thermocouples and temperature compensated strain gauge type transducers respectively. The output from these devices were continuously recorded on strip chart and/or oscillograph recorders as summarized in Table 7.

3.2.2.2 Test Objectives

The basic test objective of the subscale gas generator test series was to determine the adequacy of the proposed flight concept gas generating element when operated in conjunction with the mixed hydrazine-based fuel (TSF-1) over an ambient temperature range of -65 to +160°F. Further, the gas

BREADBOARD FUEL SUPPLY SYSTEM



SUBSCALE GAS GENERATOR TEST SCHEMATIC

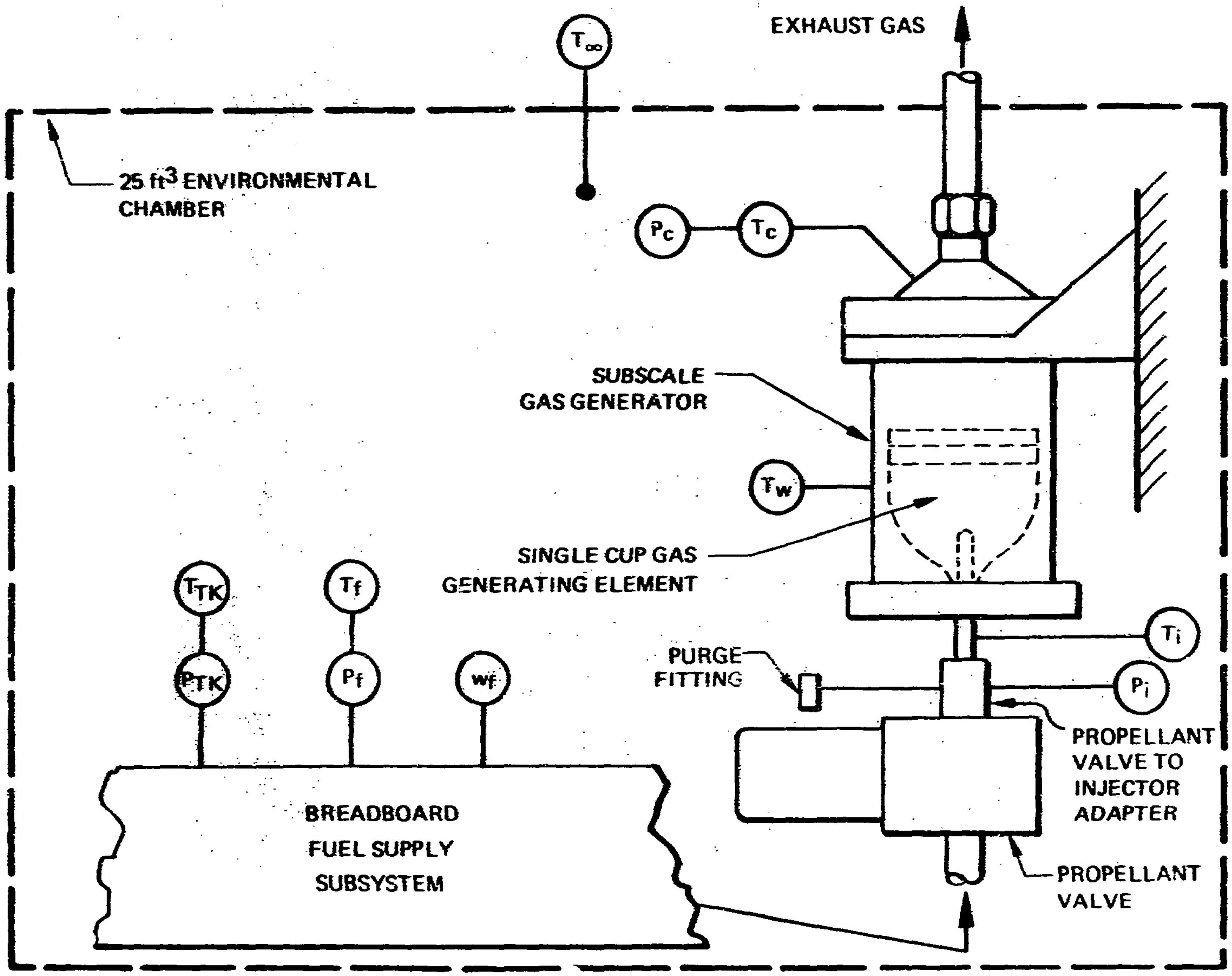


Table 7
SUBSCALE GAS GENERATOR INSTRUMENTATION

Symbol	Parameter	Range	Record on	
			Strip Chart	Oscillograph
P_c	Chamber pressure	0 to 1,500 psig	X	X
T_c	Chamber temperature	0 to 2,250°F	X	
T_w	Wall temperature	0 to 900°F	X	
T_i	Injector stem temperature	0 to 475°F	X	
P_i	Injector pressure	0 to 1,500 psig	X	X
T_{TK}	Fuel tank temperature	-65 to +160°F	X	
P_{TK}	Fuel tank pressure	0 to 1,500 psig	X	
P_f	Fuel pressure	0 to 1,500 psig	X	X
T_f	Fuel temperature	-65 to +160°F	X	
$\dot{W}_f$	Fuel flow rate	0 to 0.1 lbm/sec		X
T_∞	Environmental temperature	-65 to +160°F	X	

generating element must be capable of operating satisfactorily throughout a limited life demonstration equivalent to 20 full power starter operating cycles.

3.2.2.3 Flight Concept Gas Generating Element – As Proposed

The "as proposed" version of the flight concept gas generating element utilized a mixed catalyst bed geometry previously described. The upper catalyst bed was loaded with approximately 6 grams of 25- to 30-mesh Shell 405 spontaneous catalyst. The lower bed was loaded with approximately 8 grams of a nonspontaneous catalyst LCH-202 manufactured by RRC. The mixed catalyst bed technique was proposed to reduce the cost of the catalyst in the gas generating elements.

3.2.2.4 Test Results

A series of 39 subscale gas generator test firings were conducted to achieve the required gas generating element performance and demonstrate the limited life capability of the catalyst bed. The test results are discussed below.

Subscale testing was initiated at ambient soak conditions with the "as proposed" mixed catalyst bed gas generating element. Five test firings were conducted at ambient soak conditions to monitor gas generator operating characteristics such as chamber pressure level and stability, ignition characteristics, gas temperature and the overall performance of the breadboard fuel supply system, and the test instrumentation and control subsystems.

The low temperature ignition characteristics of the mixed catalyst bed reactor were then evaluated by conducting multiple start attempts at 0°F soak conditions. These tests were not successful. The mixed catalyst bed design would not support ignition at 0°F. A review of the test data resulted in the conclusion that the catalyst bed was insufficiently active to support the low temperature ignition requirement.

The baseline gas generating element catalyst bed composition was changed to all Shell 405 catalyst (25 to 30 mesh); the LCH-202 cataly . was replaced with Shell 405 catalyst.

Subsequent testing of the all Shell 405 catalyst bed geometry resulted in successful ignitions at the required -65°F soak conditions.

Subscale testing was then conducted at +160°F soak conditions with successful results, and the subscale gas generator test program was then concluded by accumulating over 20 test firings on the same catalyst bed to demonstrate the contractual requirement of a limited life capability of at least 20 full power starter operating cycles.

3.3 BASELINE STARTER TESTING – CARTRIDGE MODE

In order to determine the baseline starter performance characteristics for subsequent comparison with hydrazine operation, a series of firing tests were conducted with the starter operated by a solid propellant cartridge. To sufficiently map the performance characteristics of the starter, a series of eight "cartridge mode" starter firings were conducted over an operational temperature range that varied from -65 to +160°F. These firing tests determined the starter output speed versus time characteristics (for a given load), as a function of ambient soak temperature.

The contracting agency supplied two different model cartridge starters for possible use in the test program. Both starters were of the cartridge-pneumatic type. One starter was manufactured by Garret, Model No. STU15/A34. The other starter, Model STU13/A34, manufactured by Sundstrand.

The Sundstrand starter was selected for the hydrazine starter feasibility test program because of its aerodynamic braking feature which would prevent overspeed starter damage in the event of any unforeseen loss of control in the breadboard fuel supply system during hydrazine mode starter testing. This starter, S/N 650, had been overhauled and released as serviceable by ALC/San Antonio on July 14, 1975. This starter utilized a standard 8-pound solid propellant cartridge of the MXU4/A or MXU4A/A designation for cartridge mode operation.

3.3.1 Starter Test Stand

Starter output speed versus time operating characteristics were monitored with a government-furnished universal starter test stand, P/N 53E36-44D, Federal Stock No. 4920-803-7035, manufactured by Bendix. The test stand is a semiportable, self-contained unit that includes all of the equipment necessary to test a broad range of fuel-air, cartridge or pneumatic starters.

The primary component of interest in the universal starter test stand is the provision for loading the cartridge starter by means of an inertial wheel system to simulate a jet engine starting load. The effective inertia of the starter load is 13.7 slug ft^2. The inertia wheel is equipped with a tachometer for monitoring flywheel (starter output shaft) speed.

The technical order for the universal starter test stand (T.O. 3304-6-169-1) contained detailed instructions for the installation and checkout of the test stand prior to use. Time to terminal speed curves for various starter configurations were also presented for accept/reject criteria for starters to be tested on the universal starter test stand. The time to terminal speed curve for the STU13/A34 starter, from the reference T.O., is shown in Figure 27.

For acceptable starter performance, the starter terminal speed must be on or to the right of the line shown. Minimum terminal speed was *not* defined, nor was there any reference to the range of ambient soak temperature allowable, although the allowable operating temperature range for the test stand itself was listed as +40 to +130°F.

Figure 28 is a photograph of the STU13/A34 cartridge starter installed on the appropriate test pad on the universal starter test stand. It should be noted that this particular starter mounts such that the cartridge breech is oriented vertically down. The exhaust ducting is an assembly of "accessory" items available for the universal test stand.

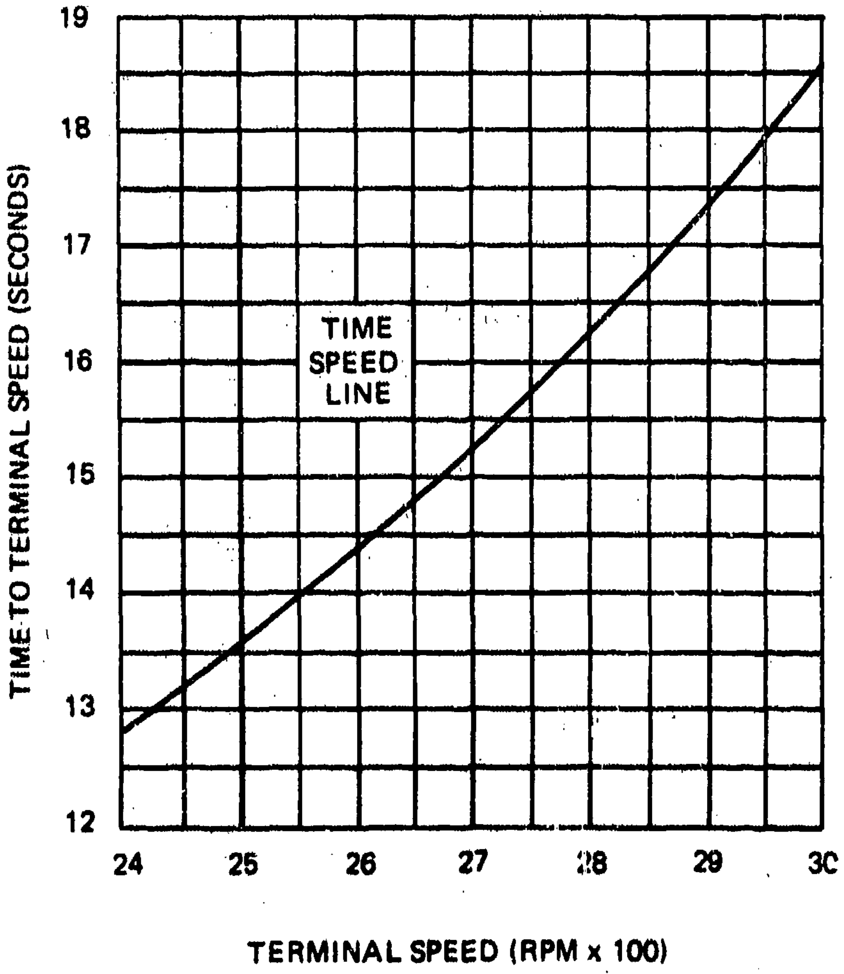
Table 8 depicts the testing sequence for the eight shot cartridge mode baseline starter performance test series. Also shown are the applicable RRC test run numbers and the ambient soak temperature of the starter and the solid propellant cartridge prior to firing. The entire eight run series utilized MXU4A/A cartridges manufactured by Talley in the February, May, or June 1967 time frame.

Table 8

CARTRIDGE MODE TEST SUMMARY

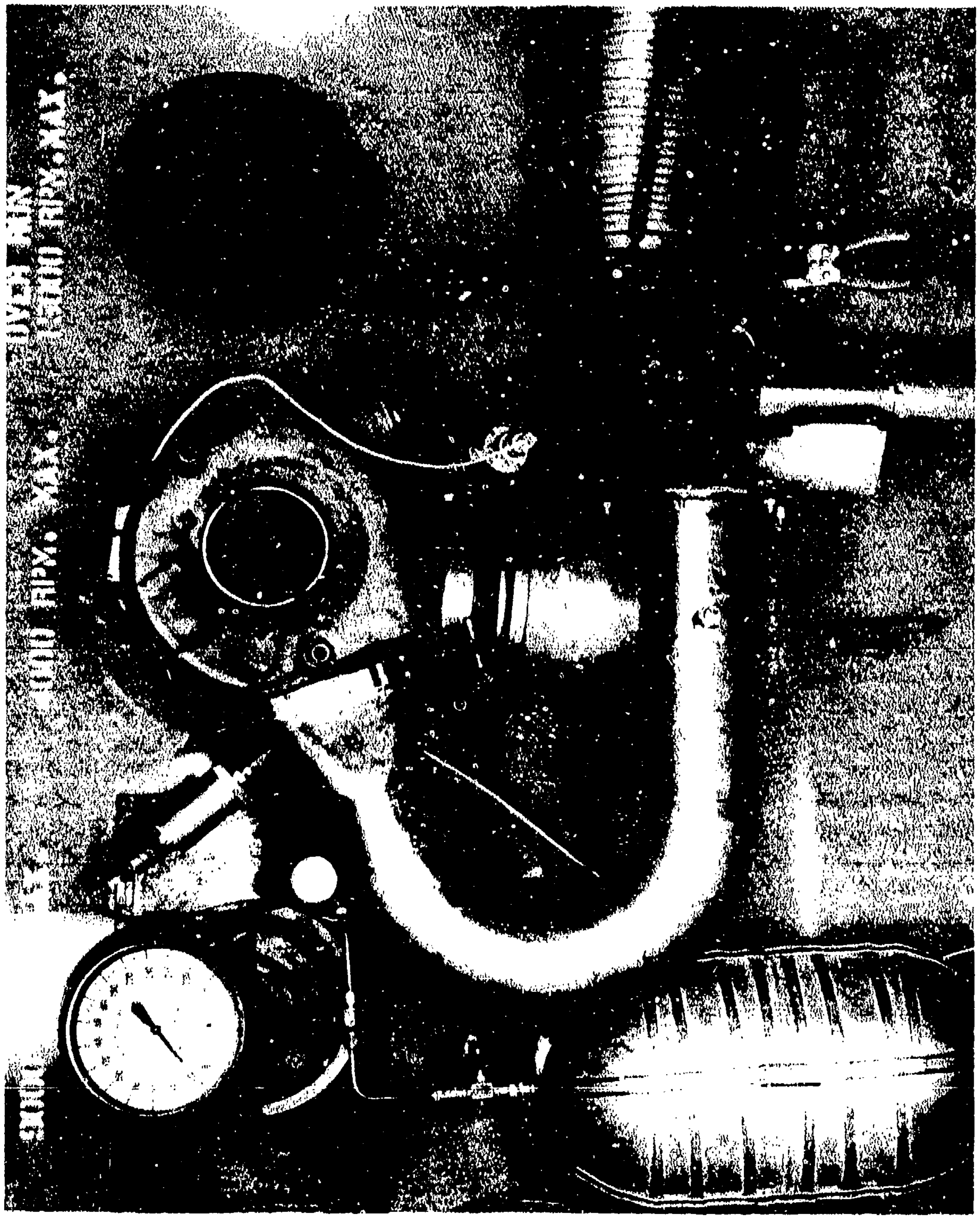
Test Sequence Number	RRC Run Number	Ambient Soak Temperature, °F	Talley Cartridge	
			Mfg Date	Lot Number
1	40	+55	6-67	TI-2-128
2	41	+55	6-67	TI-2-128
3	42	+55	6-67	TI-2-128
4	43	+160	2-67	TI-1-198
5	44	+160	2-67	TI-1-198
6	45	-65	2-67	TI-1-198
7	46	-65	2-67	TI-1-198
8	47	+55	5-67	TI-2-98

UNIVERSAL STARTER TEST STAND
ACCEPTANCE CRITERIA – STU 13/A4



TIME TO TERMINAL SPEED CURVE FOR STU 13/A34 STARTER

CARTRIDGE STARTER INSTALLATION ON UNIVERSAL STARTER TEST STAND



The test setup for the cartridge test firings is shown in Figure 29. The basic test setup included the starter, the universal starter test stand, and a 25-ft^3 environmental chamber that was utilized to temperature condition the starter and its solid propellant cartridge prior to testing at the -65 and +160°F test conditions.

The starter was instrumented as shown in Figure 29. Two pressures were measured with temperature compensated strain gauge type transducers, the breech pressure P_c, and the exhaust duct pressure P_{ex}. Five temperatures were monitored with chromel/alumel thermocouples; the temperature of the solid propellant gas in the breech, T_c, the exhaust gas temperature immediately downstream of the starter exhaust flange T_{ex}, and three external starter skin temperatures T_b, T_w, and T_m. T_b is the temperature of the breech base at a point near the manifold joint that connects the breech to the turbine hot gas nozzles. T_w is the temperature of the cartridge breech cap, and T_m is the temperature of the starter manifold immediately adjacent to the hot gas nozzle block just upstream of the turbine wheel.

The universal starter test stand was equipped with a magnetic pickup on the flywheel for monitoring flywheel speed. The pulsing signal from the magnet was converted to an analog voltage output, and a panel meter was available for monitoring flywheel speed. Rocket Research Corporation recorded the analog signal (N) remotely on a strip chart recorder to obtain permanent recordings of flywheel speed versus time.

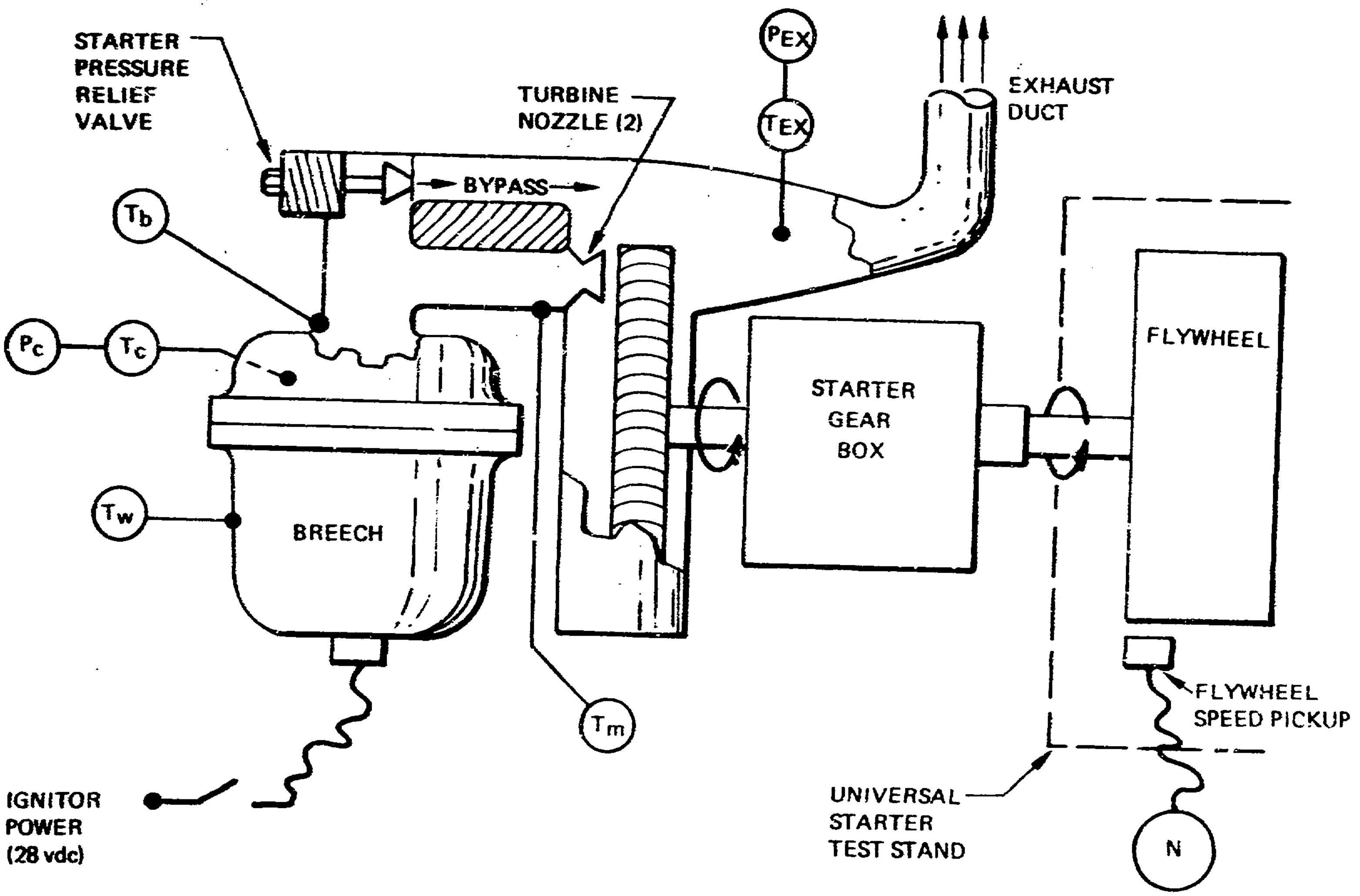
As noted, the operational temperature range for the universal starter test stand was listed in the T.O. as +40 to +130°F. Since it was required to operate the cartridge starter at temperature extremes considerably beyond these limits (i.e., -65 and +160°F), the tests were conducted by removing the starter from the universal test stand and temperature conditioning the starter and the solid propellant cartridge in a remote environmental chamber prior to conducting the test.

The breech cap was removed from the starter. The starter, breech cap, and solid propellant cartridge were then installed in the environmental chamber. Thermocouples were attached to these three components, and the temperature of the environmental chamber was adjusted to the desired test level. The component thermocouples were then monitored. The components remained in the environmental chamber for at least 4 hours subsequent to indicated temperature stabilization at the required soak temperature.

The starter was then removed from the environmental chamber and installed on the test pad of the universal test stand. This operation involved moving the starter approximately 6 feet from the environmental chamber to the test stand, installing a Marmon clamp at the starter/stand mounting pad, installing a Marmon clamp at the starter/exhaust duct joint, attaching the P_c transducer, and connecting three thermocouple plugs T_c, T_b, and T_m. This operation took approximately 2 to 3 minutes.

The solid propellant cartridge was then installed in the starter breech cap, and the resultant assembly was removed from the environmental chamber and installed on the starter breech base. The ignitor power and breech wall thermocouple (T_w) plugs were connected, and the starter was operated within the next 60 to 90 seconds.

TEST SET-UP "BASELINE STARTER PERFORMANCE, CARTRIDGE MODE"



The starter turbine wheel was cleaned after each starter operating cycle by blowing a mixture of compressed air and hot water through the pneumatic air supply inlet fitting on the starter, followed by oven drying.

The effectiveness of this cleaning technique was apparently adequate since the test results of the eighth starter firing were in excellent agreement with the first starter firing, and both of these tests were conducted at an ambient soak temperature of +55°F.

3.3.2 Test Results

The primary starter performance data of interest from the cartridge firings was the terminal speed of the starter output shaft (flywheel speed), the time required to reach terminal speed, and the manner in which these parameters varied with ambient soak temperature. These test results are plotted in Figure 30.

Referring to Figure 30, it is noted that the time to terminal speed increased as the ambient temperature decreased. This trend and the times involved were consistent with the anticipated test results.

The trend of increasing terminal speed with decreasing ambient temperature was directly opposite to the anticipated test results.

It is interesting to compare the test results at +55°F (Sequences 1, 2, 3, and 8) with the accept/reject criteria from the universal starter stand T.O., Figure 27. Sequences 1, 2, and 8 are acceptable; Sequence 3 indicates substandard starter performance.

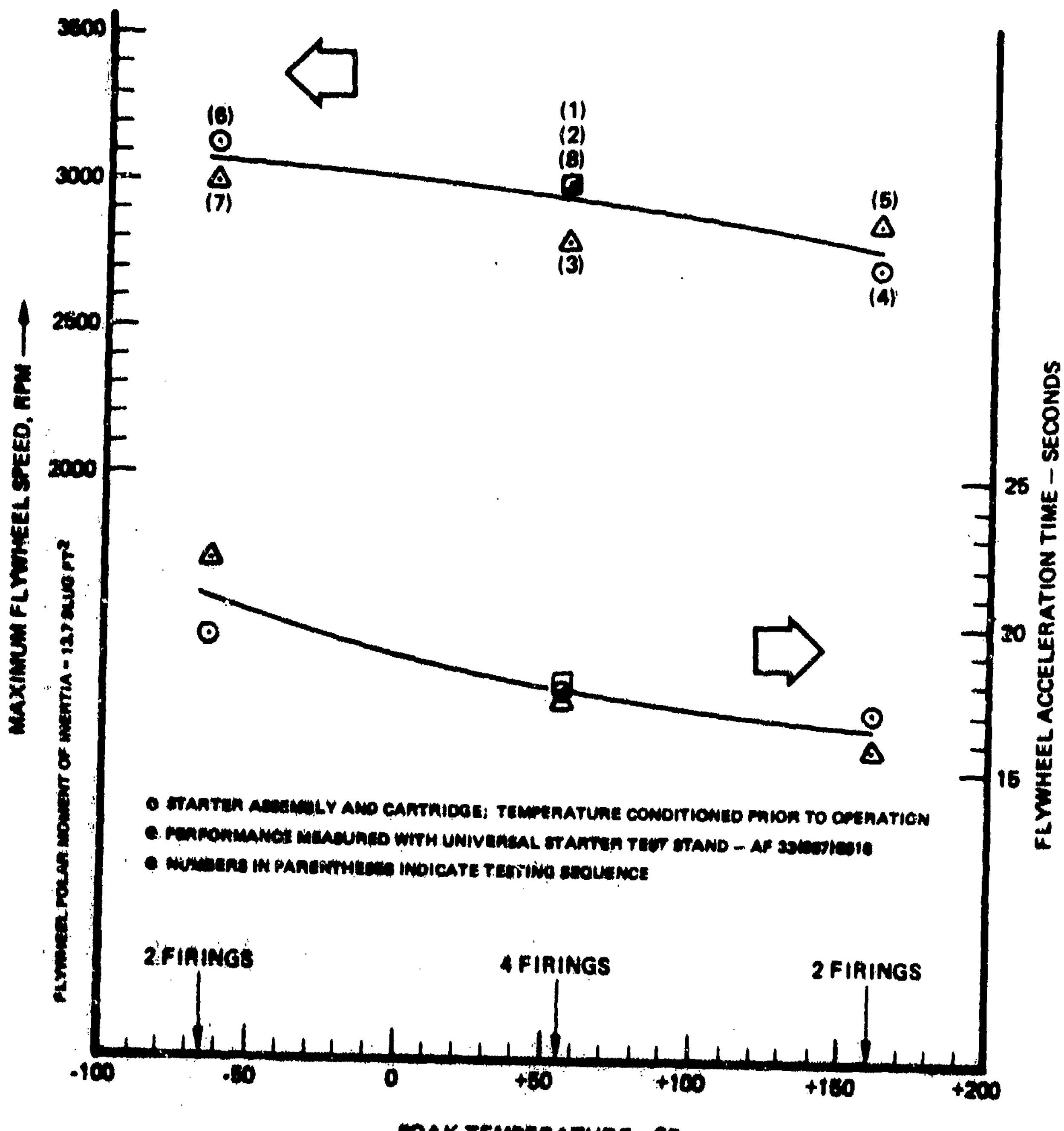
Figures 31 through 33 are overlay tracings of the flywheel time/speed and breech pressure versus time recordings for typical test runs from the "cartridge mode" baseline test series at temperatures of +55, +160, and -65°F respectively. Each figure also includes the total value of the breech pressure, time integral from ignition to burnout, and the average value of the breech pressure from ignition to the time to terminal speed.

Figure 34 is an overlay tracing of the major parameters recorded during test Sequence 2 (run 41 at ambient soak conditions). Figure 34 shows the relationship between breech pressure (P_c), starter speed (N), gas temperature in the breech (T_c), turbine exhaust gas temperature (T_{ex}), and the turbine exhaust duct static pressure (P_{ex}) during a typical cartridge mode starter operating sequence.

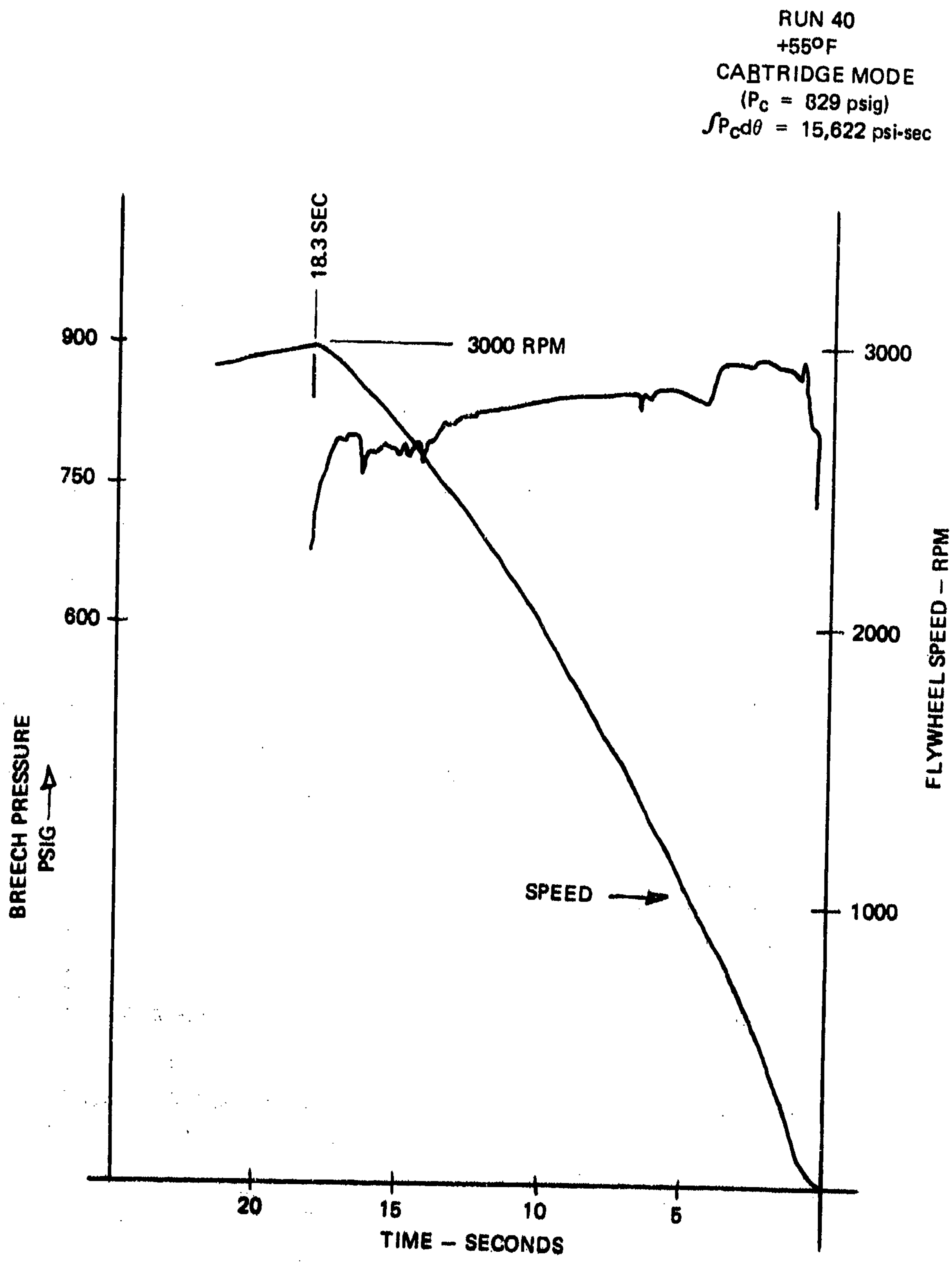
The peak gas temperature (T_c) measured in the cartridge breech during run 41 was 1,887°F; the maximum gas temperature noted during the eight run test series was 2,222°F (run 44) at an ambient soak temperature of +160°F.

The peak exhaust gas temperature (T_{ex}) as measured during run 41 was 905°F. It is noted that the peak occurs relatively early in the start sequence, then the exhaust gas temperature drops. This

BASELINE STARTER PERFORMANCE
(CARTRIDGE MODE)



BASELINE STARTER PERFORMANCE CARTRIDGE MODE



24002-15

Figure 31

BASELINE STARTER PERFORMANCE CARTRIDGE MODE

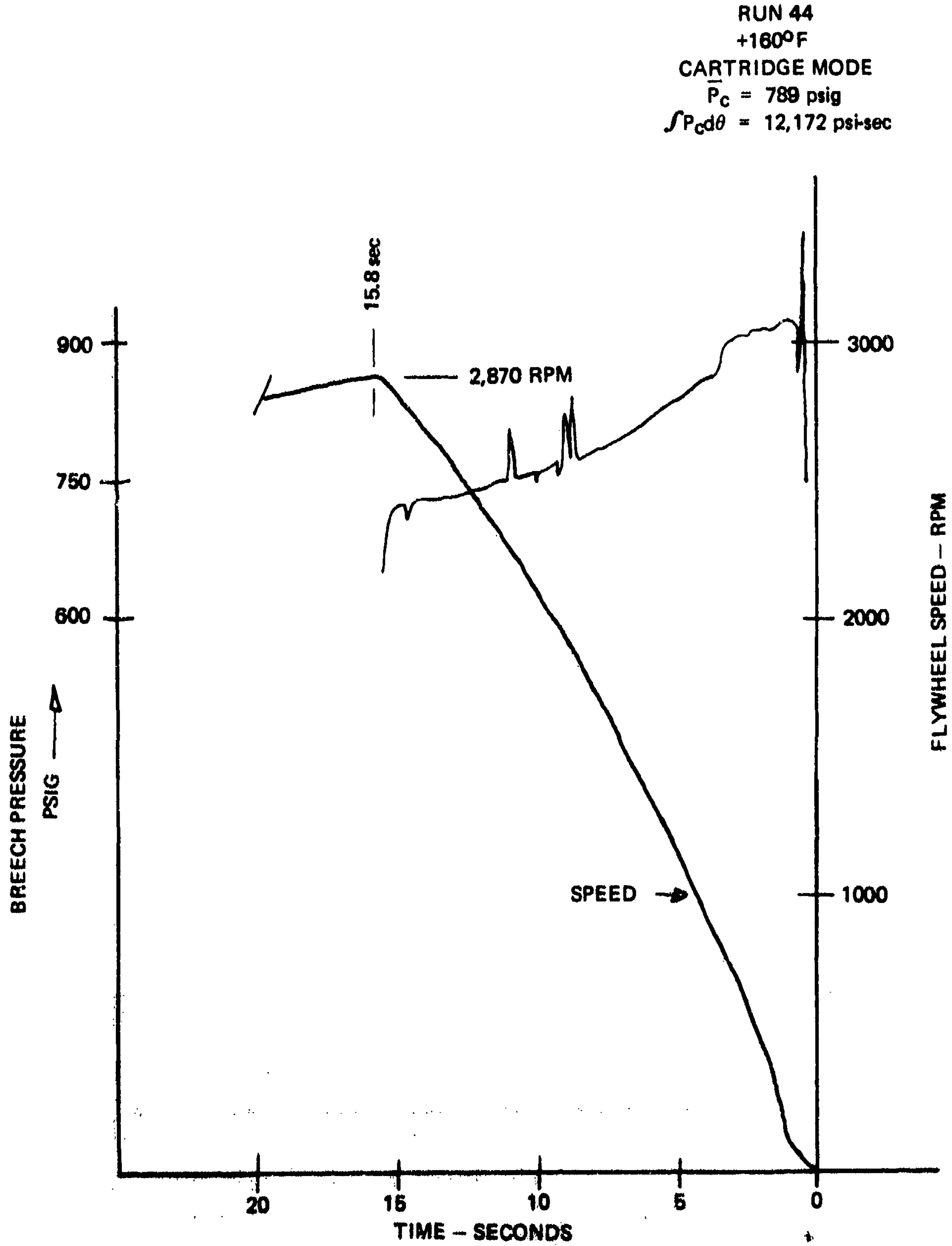
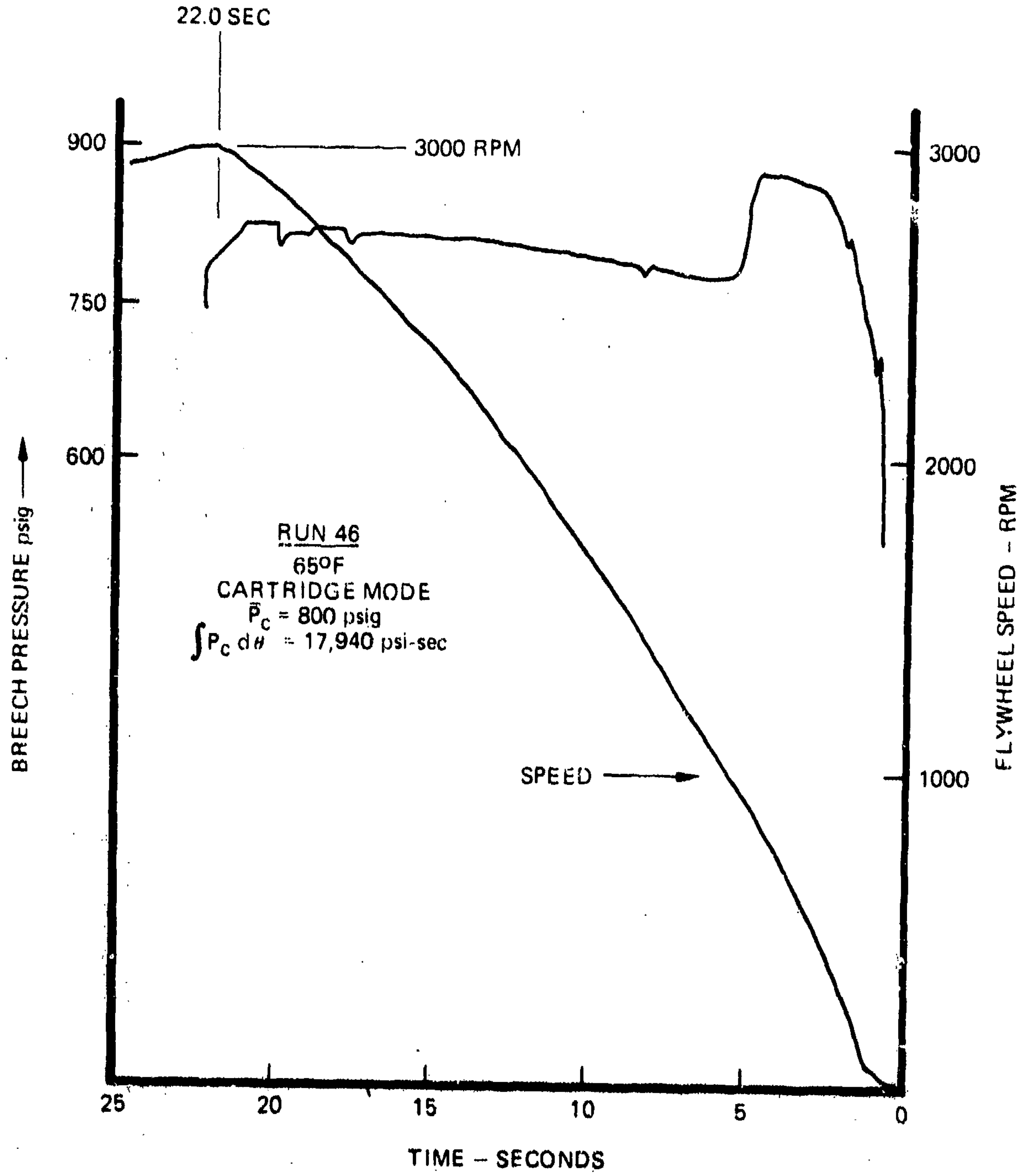
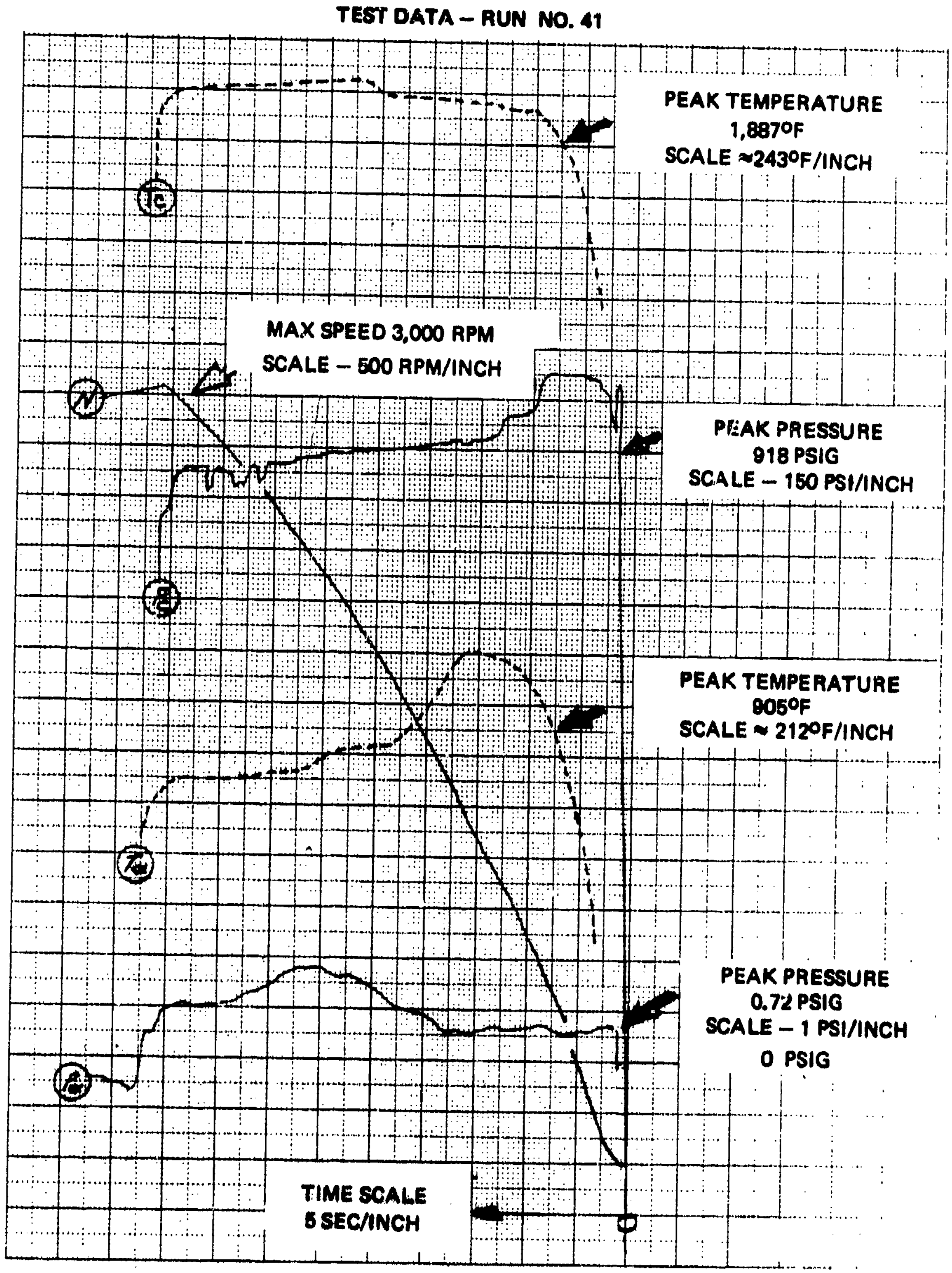


Figure 32

TYPICAL 65°F STARTER OPERATING CHARACTERISTICS
(CARTRIDGE MODE)





24002-17

Figure 34

characteristic is attributed to increased power extraction from the exhaust gas as the turbine efficiency increases during the later portion of the flywheel spin-up. The maximum exhaust gas temperature measured during the eight run test series was 1,480^{o}F (run 44) at an ambient soak temperature of +160^{o}F.

The static pressure in the exhaust duct (P_{ex}) peaked at 0.72 psig during run 41. The exhaust duct pressure was typically noted in the 0.7- to 1.0-psig range for all starter tests.

3.3.3 Discussion of Test Results

As noted in the previous section, the maximum flywheel terminal speeds were recorded at -65^{o}F test conditions. A review of the test data reveals no particular correlation between terminal flywheel speed and either the average value of the breech pressure (P_c) or the time integral of breech pressure ($\int P_c d\Theta$).

As shown in Figure 35, there is a definite trend toward decreasing average chamber pressure, terminal flywheel speed, and the pressure time integral when these parameters are nondimensionalized and plotted against ambient soak temperature. It is concluded that the terminal speed of the STU13/A34 starter, as tested, is strongly influenced by the operation of the pressure relief valve that is located between the starter breech and the starter turbine nozzle block. It appears that this valve bypasses ever increasing amounts of breech gas around the turbine nozzle block as the ambient soak temperature (prior to starter operation) is increased.

Starter operation in the "cartridge-mode" resulted in the formation of a large cloud of black smoke. Figures 36 and 37 are sequential photographs of the smoke cloud taken approximately 2 seconds and 10 seconds, respectively, after starter initiation during run 43 (Sequence 3). The exhaust duct is 10 inches in diameter, discharging vertically-up.

After the completion of all scheduled Phase II testing, RRC conducted a 12 run "cartridge-mode" starter firing test series at ambient soak temperature conditions to allow AFRPL personnel to sample the starter exhaust products for exhaust gas composition analysis.

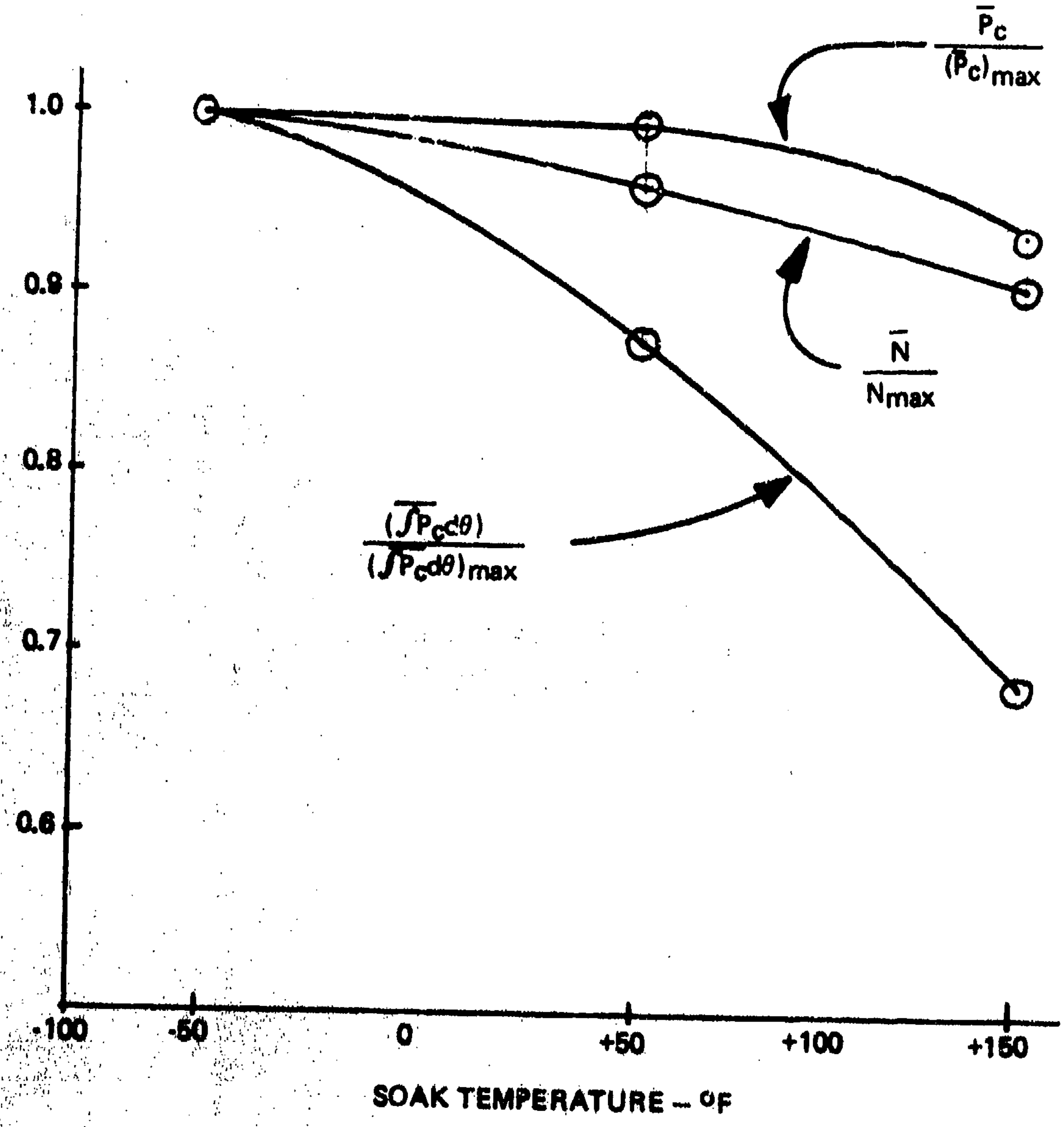
Specific details of this test series and the results of the exhaust gas analysis are the subject of an official report prepared and distributed separately by the AFRPL organization.

For the purpose of this report, the 12 run test series provides additional test data on the operating characteristics of the STU13/A34 starter in the cartridge mode at ambient soak temperature conditions.

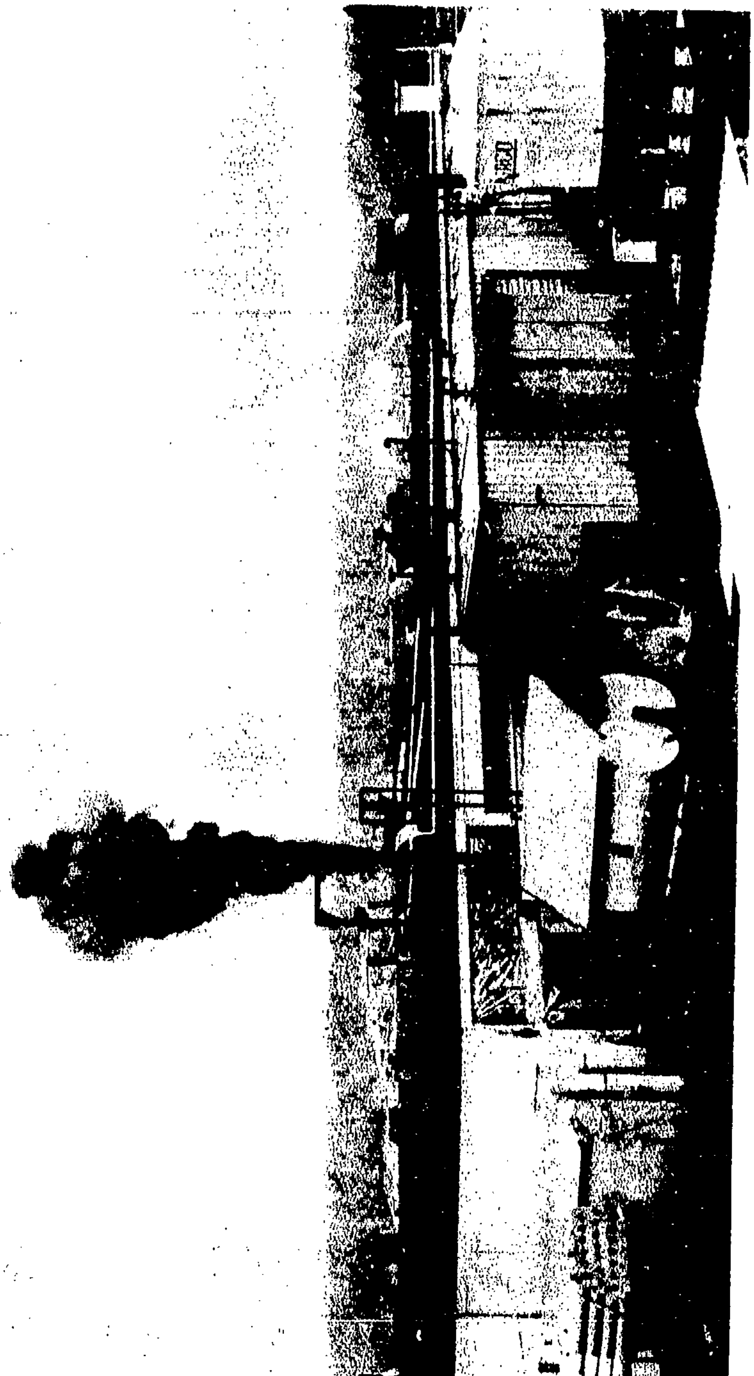
In gross terms, the 12 run AFRPL test series resulted in ambient temperature "cartridge-mode" starter performance that was consistent with the results obtained during RRC's previous baseline starter test series.

It should be noted that the AFRPL test series was conducted with the same cartridge starter that had been used to accumulate eight baseline "cartridge-mode" firings and 32 hydrazine-fueled starter operating cycles.

BASELINE STARTER PERFORMANCE (CARTRIDGE MODE)



CARTRIDGE STARTER EXHAUST PLUME — CARTRIDGE MODE



CARTRIDGE STARTER EXHAUST

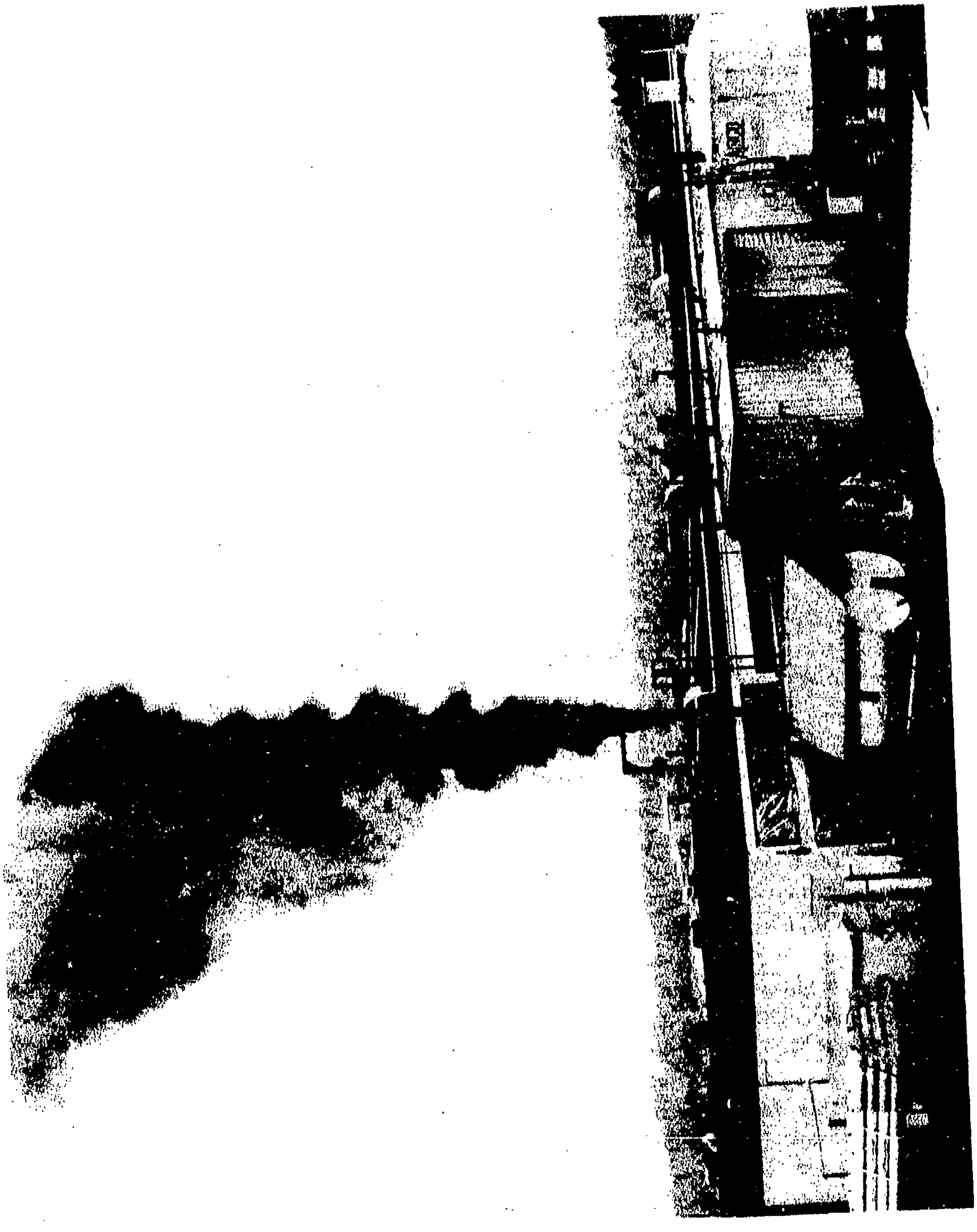


Figure 37

The cartridges used during the AFRPL tests were as follows:

a. Runs 90 through 93, Olin, Lot OL-10-237, manufactured May 1967
b. Runs 94 through 97, Olin, Lot OL-13-46, manufactured September 1973
c. Runs 98 through 101, Talley, Lot TI-2-98, manufactured May 1967

Typical starter performance with each of the above solid propellant cartridge lots is summarized in Figures 38 through 40. The Talley cartridges resulted in an average terminal starter speed that was slightly higher than the Olin cartridge (2,918 versus 3,033 rpm). Additionally, it was noted that the Talley cartridge produced more smoke in the exhaust than either of the Olin cartridge lots. The September 1973 lot of Olin cartridges appeared to be the least smoky of the three cartridge lots fired.

3.4 HYDRAZINE STARTER TESTING

This section describes the flight concept version of the gas generator, its installation into the breech base of the STU13/A34 starter, and the test program that was subsequently conducted to characterize the operation of the hydrazine fueled starter.

3.4.1 Gas Generator Design

Figures 41 through 44 are photographs of the flight concept type gas generator that was fabricated for evaluation on the current program.

Figure 44 is a photograph of the flight concept gas generator assembly taken prior to the final assembly of the unit. The figure shows the "as received" configuration after oven brazing. All braze joints were made during one oven braze cycle, i.e., the eight individual cups were brazed to the baseplate, eight penetrating injector tubes were brazed into the eight cups, and the 16 joints on the eight fuel manifolding tubes were all brazed simultaneously and successfully without special tooling or fixturing. The material of all component parts was 347 series stainless steel. The braze material was Palniro I.

Figure 42 is the back side of the flight concept gas generator assembly shown in Figure 41. The fuel inlet stub is located on the axis of symmetry. The eight holes noted at mid-span in the baseplate are the pilot mounting holes for the cups.

Figure 43 is a photograph of the unit after the catalyst was loaded into the eight gas generating elements (cups). The catalyst bed and catalyst retaining bedplates have been installed, and the closure plug has been welded into the fuel manifold cavity.

Figure 44 shows the unit completely assembled with the central and peripheral heat shields installed. The central heat shield is a slotted, inverted can structure that protects the individual fuel manifolding tubes from the direct impingement of the hot gas generated from the eight gas generating elements. The peripheral heat shield is a cylindrical shell that reduces the heat load into the starter breech shell immediately opposite each of the eight cups.

STARTER PERFORMANCE CARTRIDGE MODE

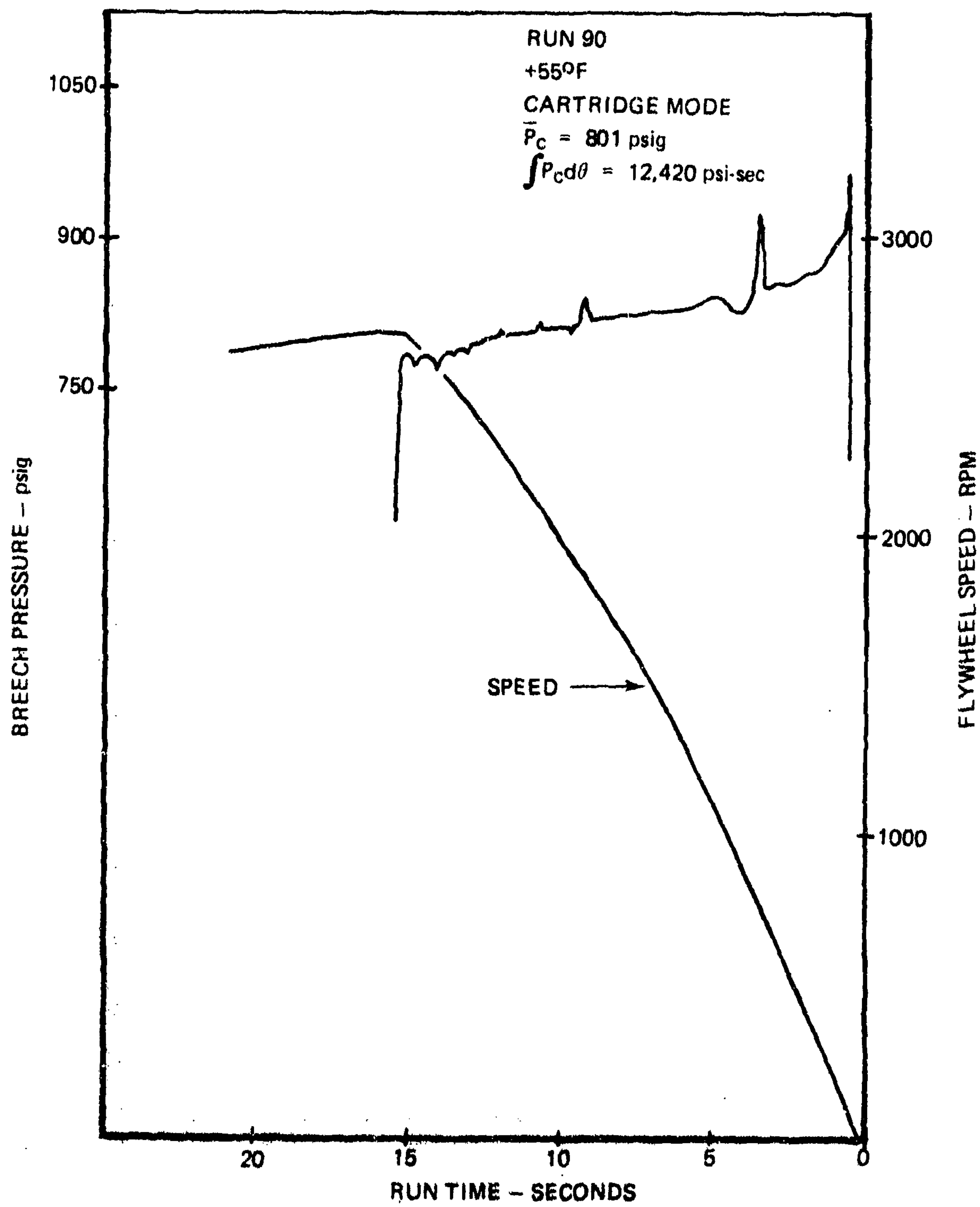
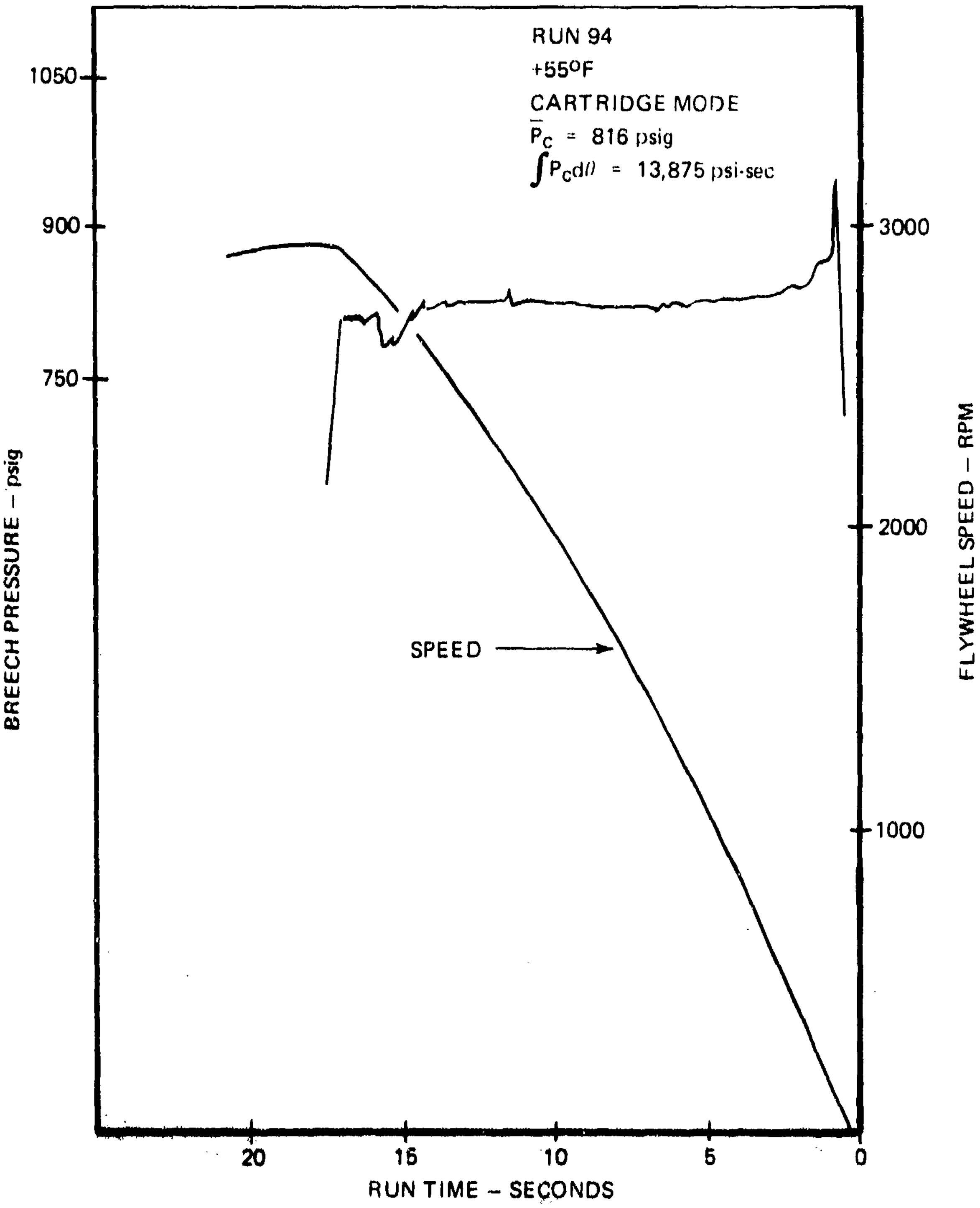
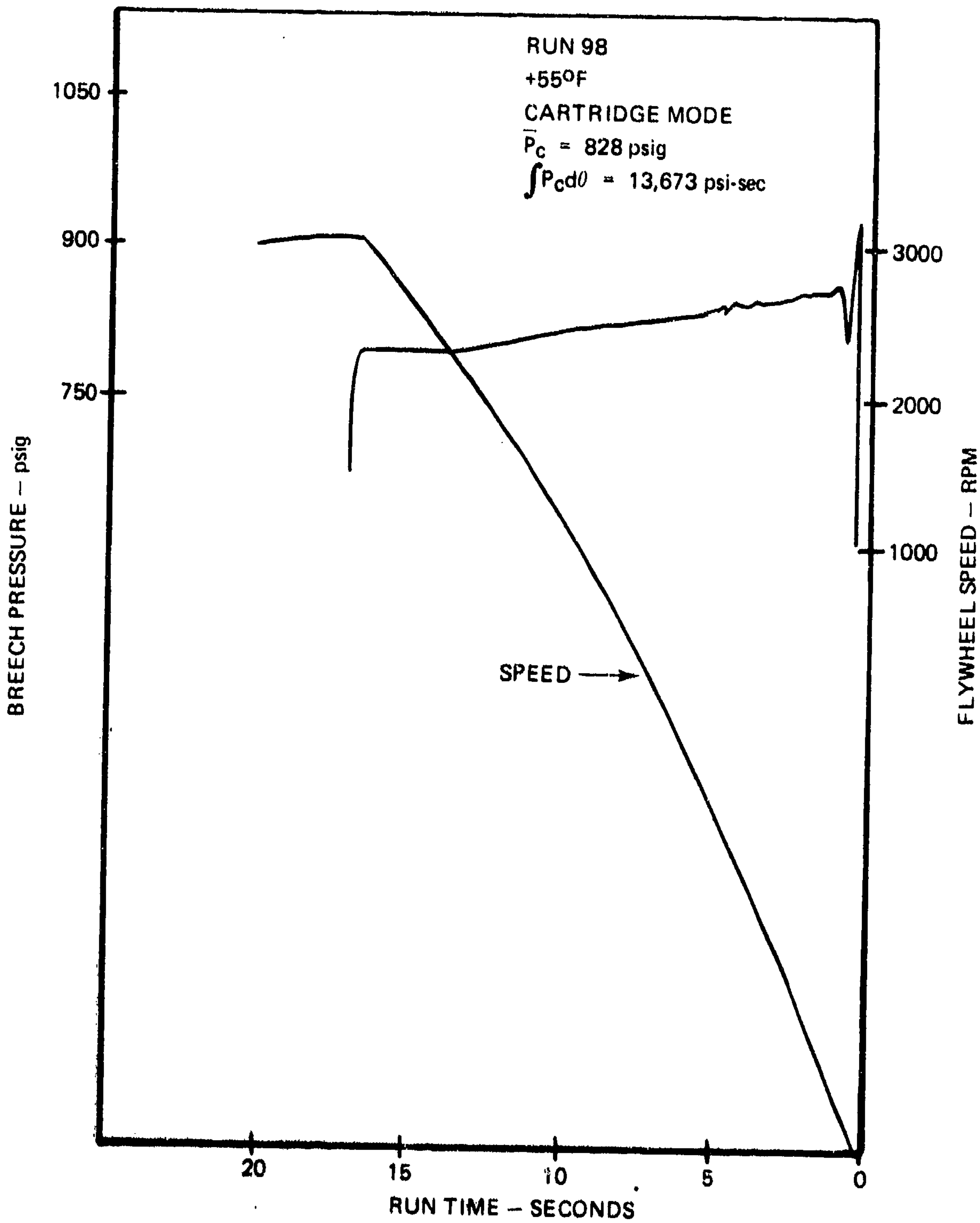


Figure 38

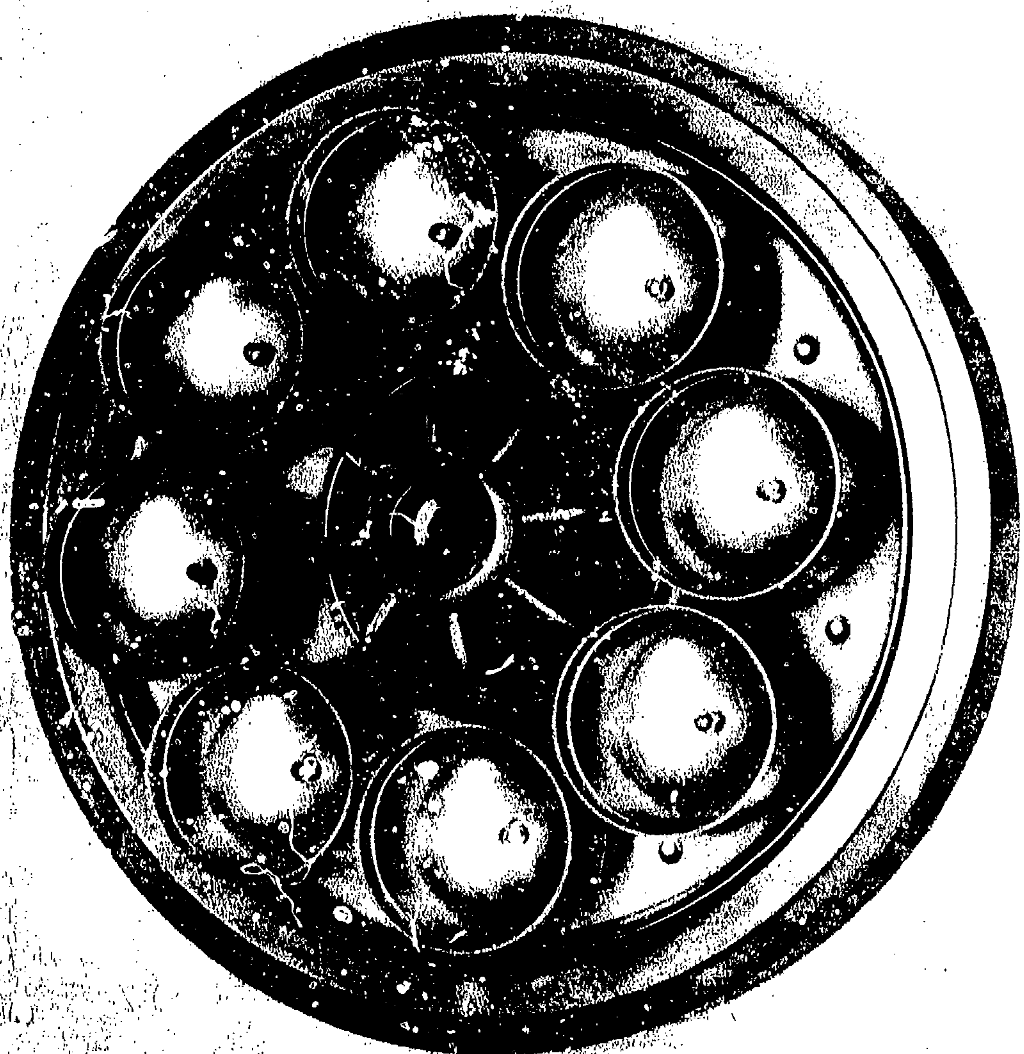
STARTER PERFORMANCE CARTRIDGE MODE



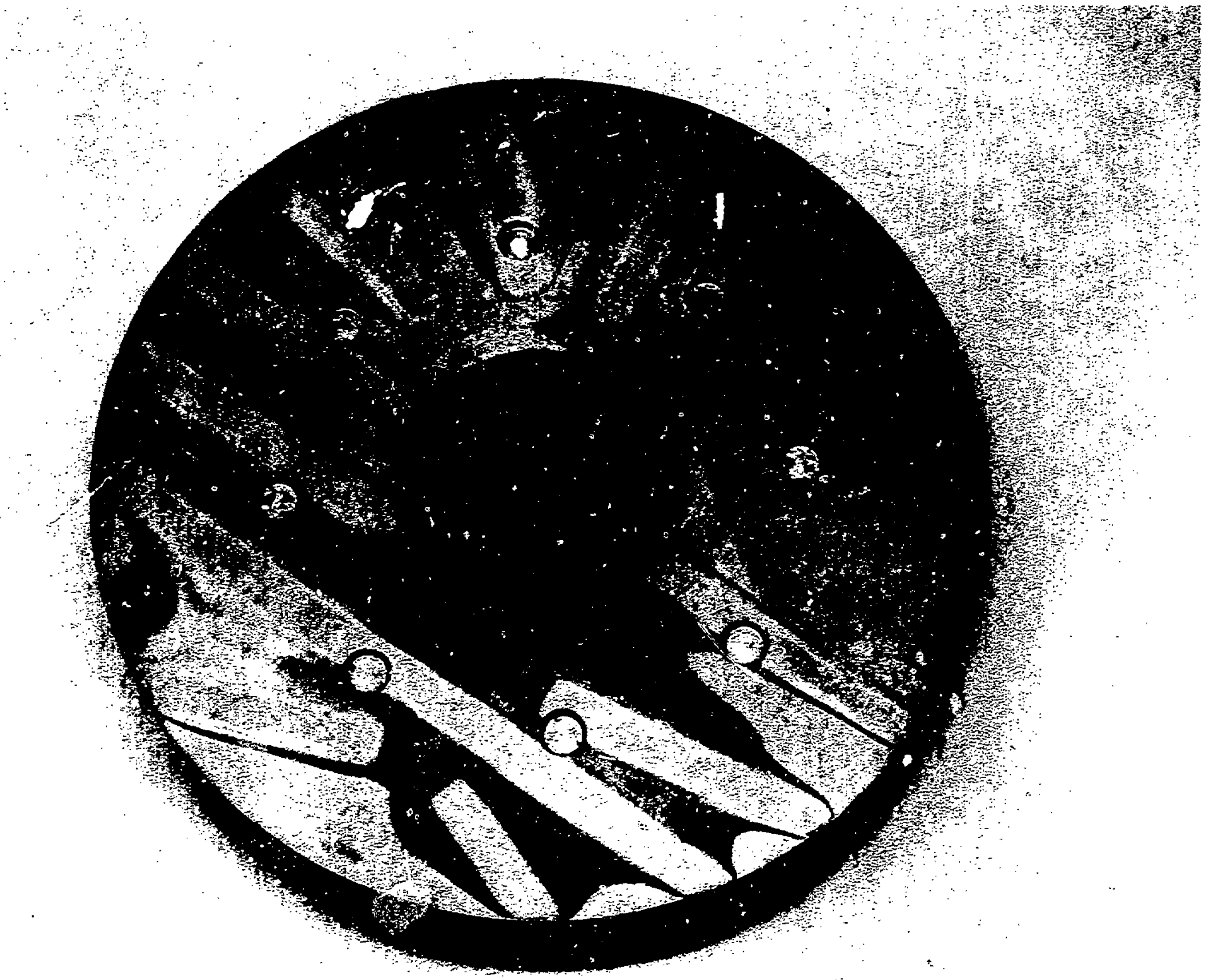
STARTER PERFORMANCE CARTRIDGE MODE



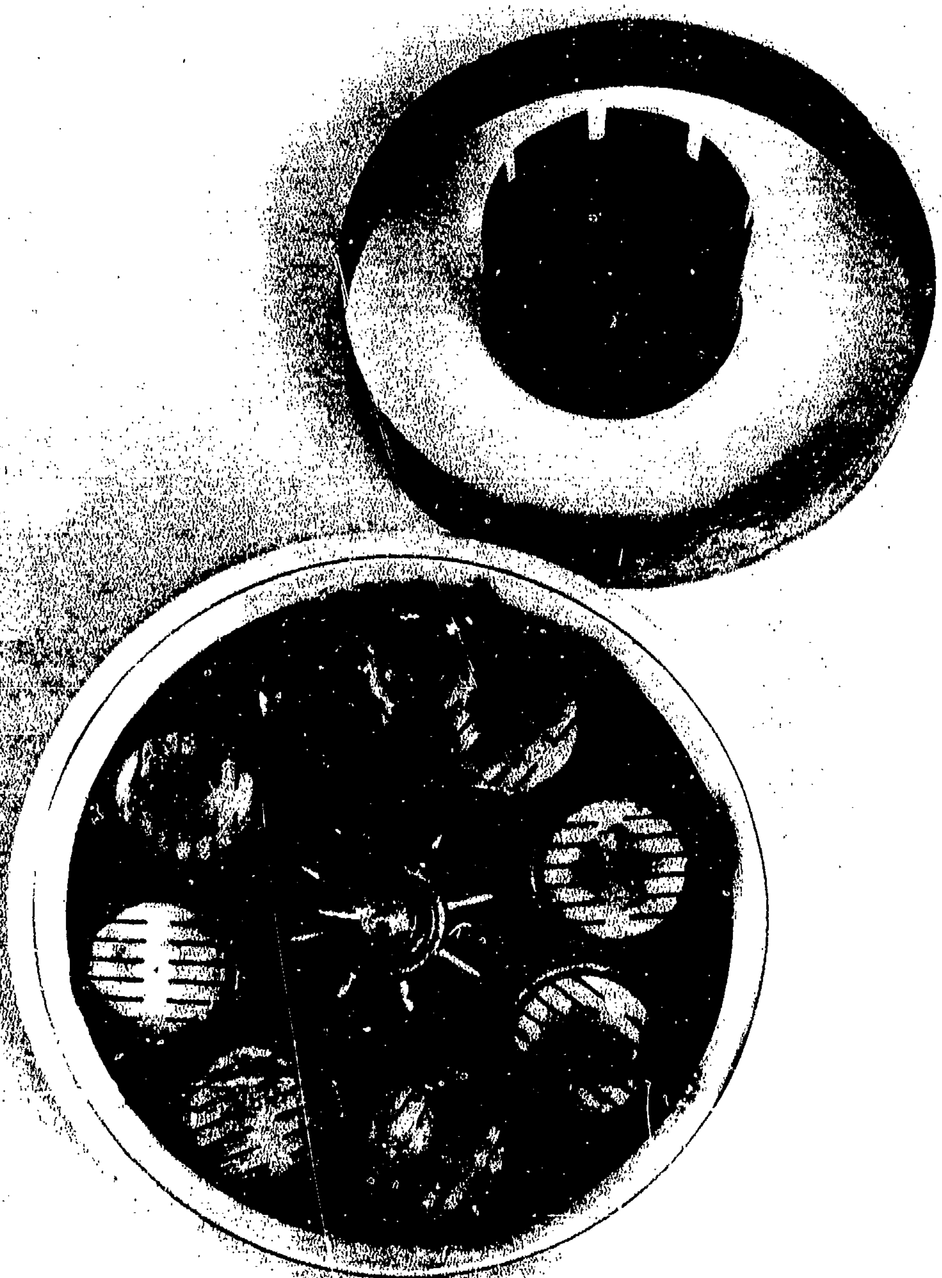
FLIGHT TYPE GAS GENERATOR (8 CUP) AFTER OVEN BRAZING

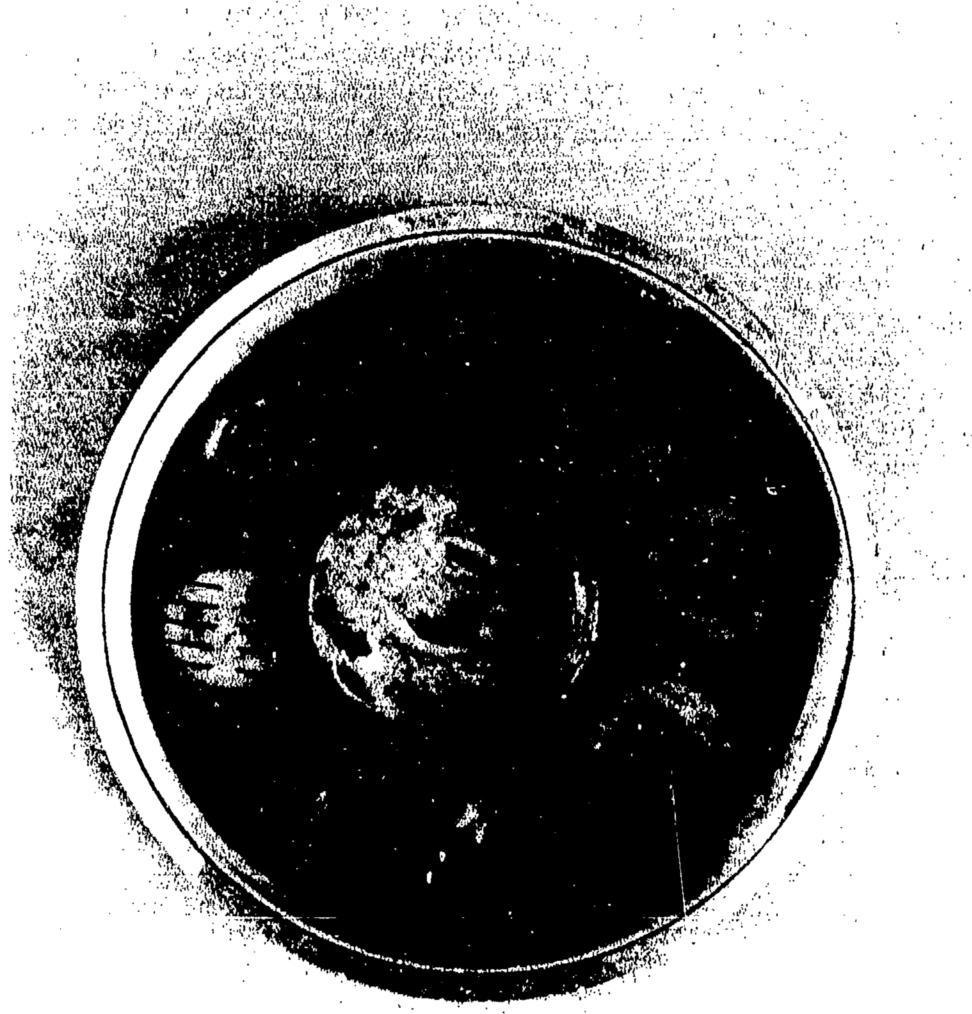


FLIGHT CONCEPT GAS GENERATOR ASSEMBLY AFTER BRAZING
(FUEL INLET SIDE)



FLIGHT CONCEPT GAS GENERATOR





FLIGHT CONCEPT GAS GENERATOR

11102-19 1840-9

Figure 44

The flight concept type gas generator assembly was adapted to the breech base of the STU13/A34 cartridge starter as shown in Figures 45 through 48.

Figure 45 is a photograph of the STU13/A34 cartridge starter, flight concept gas generator and the gas generator installation adapters prior to assembly. Left to right are the starter with its breech cap removed to show the breech base, the eight-cup flight concept gas generator, a sealing adapter, and the breech lock propellant valve adapter.

Figure 46 shows the flight concept gas generator installed in the starter breech base. The coiled wire and plug on the fuel inlet side of the gas generator is a thermocouple that is used to monitor the temperature of the injector stem of the gas generator during test.

Figure 47 shows the sealing adapter installed on top of the gas generator. The seal plate has two face seals (O-rings) that seat on the fuel inlet side of the flight concept gas generator, additionally, two peripheral seals (O-rings) seat on the I.D. bore of the breech base. The eight tapped holes near the maximum diametral surface of the sealing adapter are used to insert one or more bolts to allow seal adapter removal for access to the flight concept gas generator.

Figure 48 shows the final step in the installation process for the flight concept gas generator. The breech locking adapter plate interfaces with the starter breech through three lugs. The locking adapter is installed on top of the sealing adapter and rotated into the breech lug feature (a handle is provided to rotate the locking adapter against the compression drag of the sealing adapter face seals), a set screw is provided to prevent the locking plate from rotating during starter testing. The locking plate includes mounting provisions for the propellant valve which adapts to the fuel inlet stub on the flight concept gas generator through an O-ring sealed bayonet-type fitting.

The sealing adapter, breech locking adapter, and the propellant valve are required for breadboard starter testing and would not be used in the flight concept "in-breech" flight system.

3.4.2 Hydrazine Starter Fuel Consumption and Limited Life Demonstration

The eight cup, flight concept gas generator was installed in the breech base of the Sundstrand STU13/A34 starter as discussed in paragraph 3.4.1 and tested in conjunction with the breadboard fuel supply system (paragraph 3 1) and the government-furnished universal test stand, as described in this subsection.

Fuel consumption testing and the requirement to demonstrate a limited life capability of the flight concept gas generator were combined in the 32 full power hydrazine fueled starter tests described herein.

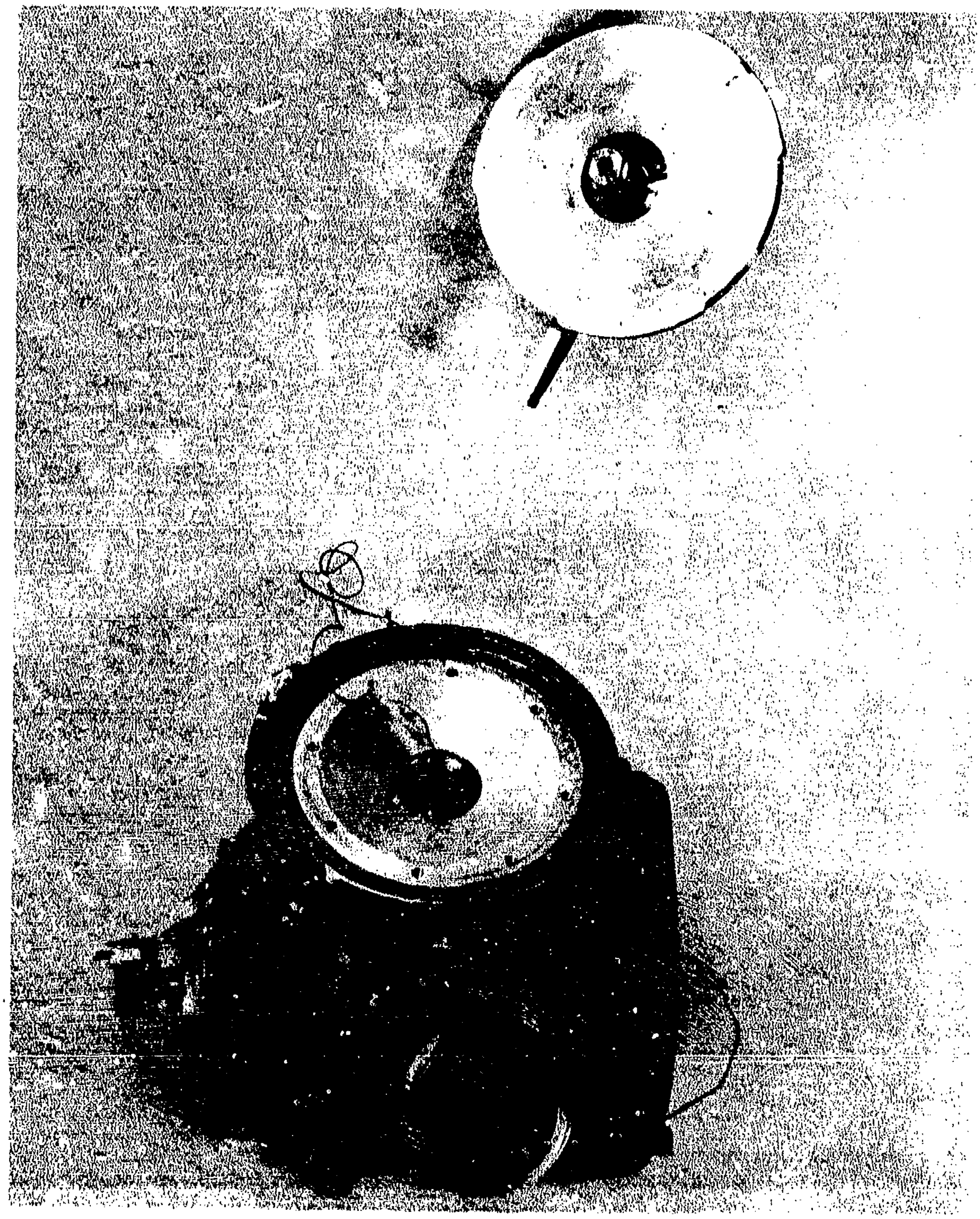
3.4.2.1 Hydrazine Starter Test Setup

Figure 49 is a photograph of the hydrazine fueled starter installation on run pad of the universal starter test stand.

HYDRAZINE FUELED STARTER COMPONENTS

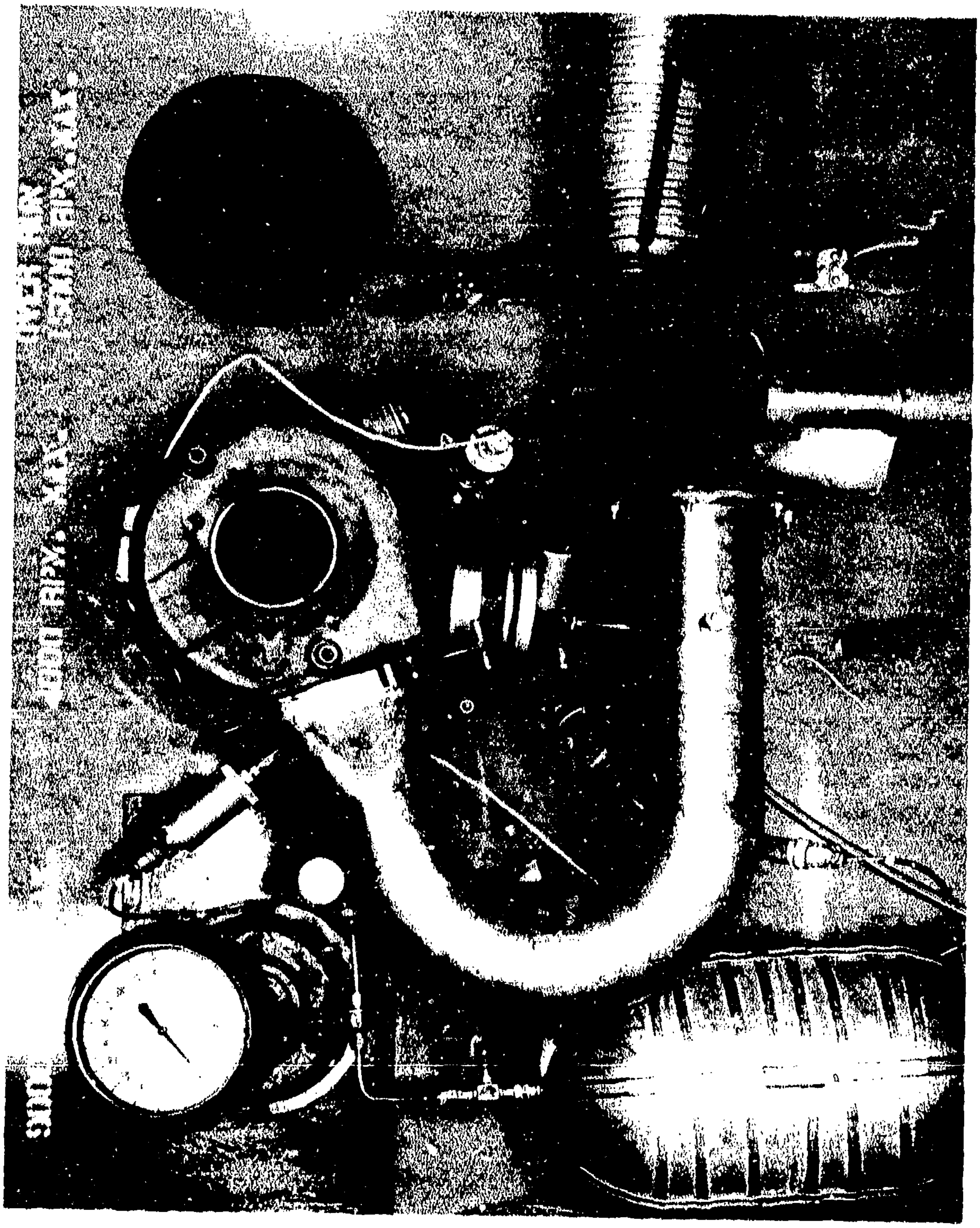
HYDRAZINE STARTER ASSEMBLY

HYDRAZINE STARTER ASSEMBLY



HYDRAZINE FUELED STARTER ASSEMBLY

HYDRAZINE FUELED STARTER INSTALLED ON UNIVERSAL STARTER TEST STAND



The flight concept gas generator is installed in the breech base of the STU13/A34 cartridge starter. Fuel is supplied to the gas generator from the breadboard fuel supply subsystem through the steel braid covered flex hose that can be seen passing behind and under the "C" shaped exhaust duct that is attached to the fan cover on the starter.

The large stainless tank and pressure gauge in the left hand portion of Figure 49 are part of the exhaust gas sampling apparatus (gas sampling is discussed in subsection 3.4.3 of this report). Three pressure transducers can be seen; the transducer at the 10 o'clock position (relative to the starter breech at 6 o'clock) is used to monitor the starter exhaust duct pressure P_{ex}. The transducer at the 4 o'clock position measures the pressure in the breech (P_c), and the transducer at the 7 o'clock position is used to monitor the fuel pressure immediately upstream of the fuel inlet stub on the flight concept gas generator.

Figure 50 is a sketch of the hydrazine fueled starter test setup. Major elements of the setup include the flight concept gas generator/starter assembly, the universal starter test stand, and the breadboard fuel supply subsystem.

For temperature-conditioned starter runs at -65 and +160°F soak conditions, the starter was removed from the test pad on the universal starter test stand and placed in the environmental test chamber. The flight concept gas generator was then removed from the starter breech but remained in the environmental test chamber with its fuel supply flex hose connected to the breadboard fuel supply. The flex hose was charged with fuel up to the propellant valve. The breadboard fuel supply, starter, and the flight concept gas generator were maintained at the required test temperature for at least 4 hours after T_i, T_m, and T_{TK} uniformly indicated that the required soak temperature had been reached. The starter was then removed from the environmental test chamber and installed on the test pad of the universal starter test stand (two marmon clamp joints) and the instrument leads connected. The gas generator assembly was then removed from the environmental test chamber and installed in the starter breech, P_i and T_i instrument plugs were connected, and the starter was operated within the next 60 to 90 seconds.

3.4.2.2 Instrumentation

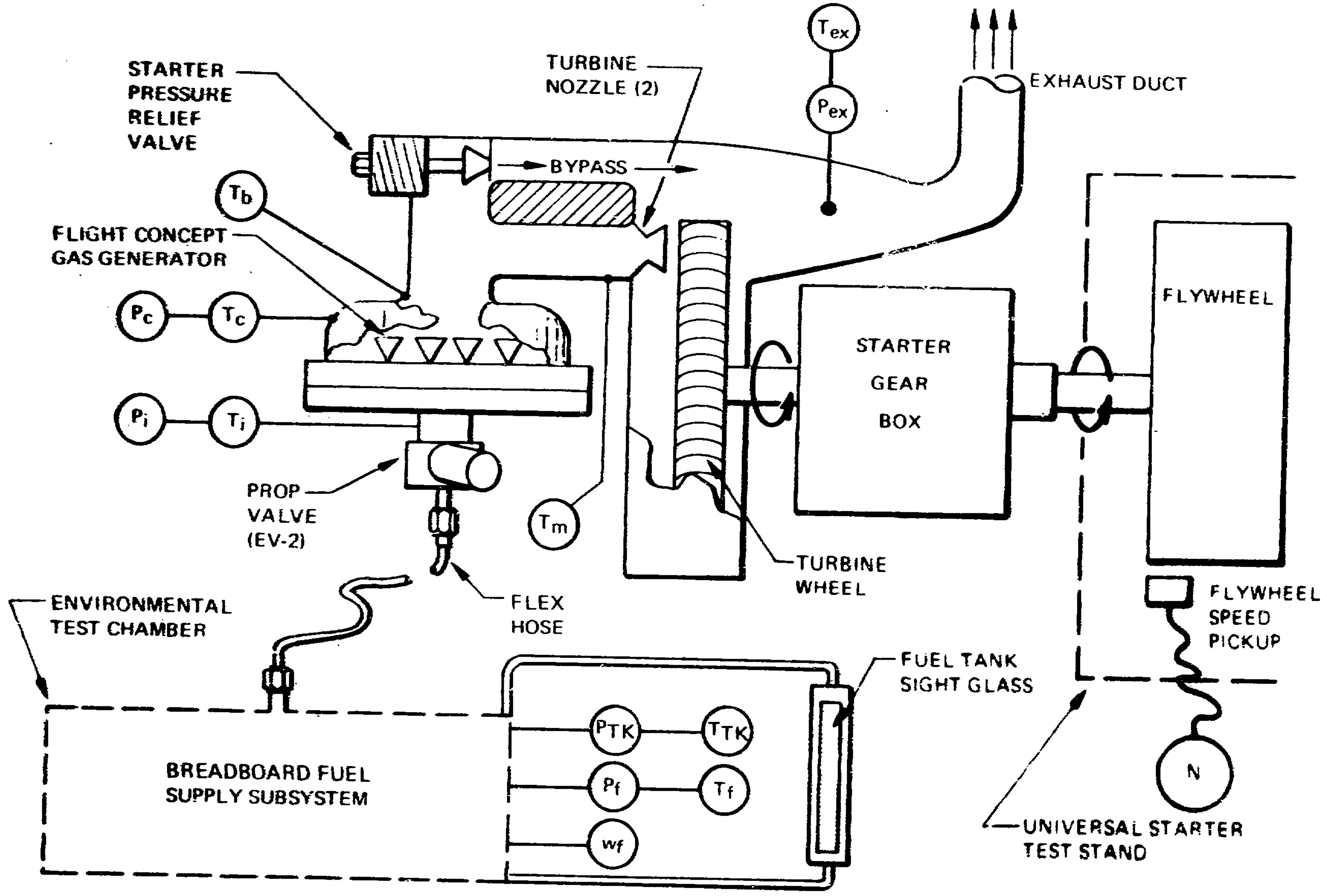
All temperatures and pressures were monitored with chromel alumel thermocouples and temperature-compensated strain gauge type transducers respectively. The output from these devices was continuously recorded with strip chart and/or oscillograph recorders as summarized in Table 9.

3.4.2.3 Test Procedure

Prior to conducting each start sequence, the fuel tank in the breadboard fuel supply subsystem was filled with the hydrazine-based fuel mix, and the fuel level and fuel temperature in the unpressurized fuel tank were recorded.

The breadboard fuel supply subsystem and the flight concept gas generator/starter assembly were then temperature conditioned (for -65 and +160°F firings only) as/if required.

TEST SET-UP HYDRAZINE FUELED STARTER TEST



24002-24

Figure 50

Table 9

HYDRAZINE FUELED STARTER INSTRUMENTATION

Symbol	Parameter	Range	Record on	
			Strip Chart	Oscillograph
P_c	Breech pressure	0 to 1,500 psig	X	X
T_c	Breech temperature	0 to 2,250°F	X	
T_i	Injector stem temperature	-65 to +475°F	X	
P_i	Injector pressure	0 to 1,500 psig	X	X
P_{TK}	Fuel tank pressure	0 to 1,500 psig	X	
P_f	Fuel line pressure	0 to 1,500 psig	X	X
T_{TK}	Fuel tank temperature	-65 to +160°F	X	
T_f	Fuel line temperature	-65 to +160°F	X	
T_∞	Environmental chbr temp	-65 to +160°F	X	
P_{ex}	Starter exhaust pressure	0 to 15 psig	X	
T_{ex}	Starter exhaust temperature	0 to 905°F	X	
N	Starter speed	0 to 5,000 rpm	X	X
V_E & V_I	Prop valve voltage/current	0 to 1 inch deflect		X
$\dot{W}_f$	Fuel flow rate	0 to 0.5 lbm/sec		X
T_m	Starter manifold temperature	0 to 475°F	X	

The hydrazine-fueled starter assembly was then installed on the test pad of the universal starter test stand. The exhaust system and all instrumentation leads were connected, and the unit was ready for test.

The fuel tank was pressurized to the required start pressure (typically 20 to 100 psig). The dome loading regulator in the pressurization ramp generator was set to the required run pressure (nominally 1,250 psig).

The instrumentation recorders were started, and the hydrazine-fueled starter was operated by simultaneously opening the propellant valve (EV_2) and the solenoid valve (EV_1) in the pressurization ramp generator.

As a general rule, the firing was terminated when the starter (flywheel) speed reached a predetermined value. The firing was terminated by closing the propellant control valve. EV_2. The maximum terminal speed of particular interest was the average value of the test results obtained (at the applicable operating temperature) during the baseline "cartridge-mode" starter performance tests (see Figure 30, paragraph 3.3). The nominal terminal speeds were 3,070 rpm at -65°F, 2,950 rpm at +55°F, and 2,790 rpm at +160°F.

The flywheel was allowed to spin-down to approximately 2,000 rpm after each starter operating cycle, and then the flywheel brake was applied.

The fuel tank was vented and allowed to temperature soak back to local ambient temperature. The post-test fuel level and fuel temperature were then recorded, and the total fuel consumption/start cycle was calculated using the sightglass data and the known density of the fuel mix.

3.4.2.4 Test Results

Thirty-two full-power hydrazine starter operating cycles were conducted, 20 at ambient soak temperature conditions, 7 at -65°F, and 5 at +160°F. Table 10 is a summary of the 32-run test series. All tests conducted were totally successful.

Figures 51, 52, and 53 are representative tracings of the breech pressure and starter output shaft speed versus run time for starter operating cycles at -65, ambient, and +160°F soak conditions with the TSF-2 fuel blend. Each figure denotes the run number, pretest soak temperature, the time-averaged value of the starter breech pressure $\bar{P}_c$, and the total value of the breech pressure-time integral from the first indication of pressure to shutdown (maximum flywheel speed).

Figure 54 is an overlay tracing of the major parameters recorded during a typical hydrazine-fueled starter test (run 62 at ambient soak conditions). Figure 54 shows the relationship between breech pressure (P_c), starter speed (N), gas temperature in the breech (T_c), turbine exhaust temperature (T_{ex}), and the static pressure in the starter exhaust duct.

The peak gas temperature (T_c) measured in the cartridge breech during run 62 was 1,580°F. (Peak gas temperatures with TSF-1 fuel mix were noted to be in the 1,600 ± 50°F range over the entire -65 to +160°F operating regime. Peak gas temperatures with the TSF-2 mix were in the 1,700 ± 25°F range.)

The peak exhaust gas temperature (T_{ex}) measured during run 62 was 895°F. (Peak exhaust gas temperatures with the TSF-1 fuel mix were noted to be in the 900 ± 50°F range over the entire -65 to +160°F operating regime. Peak exhaust gas temperatures with the TSF-2 fuel mix were in the 950 ± 50°F range.) The shape of the exhaust temperature versus time curve is similar to that noted during the baseline starter operation in the "cartridge-mode," indicating increased power extraction from the working fluid during the later portion of the starter spin-up.

3.4.2.4.1 Starter Fuel Consumption Testing

The net volume available within the flight concept preliminary design breech envelope (RRC drawing SK 5585, Rev. A) for the fuel cartridge and the pressurization subsystem is on the order of 225 in.^{3}. During the Phase I preliminary design studies, it was estimated that the worst-case fuel consumption (-65°F start) would require 6.86 lbm of TSF-1 fuel. The space required to package

Table 10
TEST SUMMARY
HYDRAZINE FUELED STARTER TEST PROGRAM

RRC Run No.	Ambient Soak Temp	Type of Test			Fuel Mix	
		Limited Life Demo	Exhaust Gas Sampling	Starter Performance	TSF-1	TSF-2
49	Amb	X		X	X	
50	Amb	X		X	X	
51	Amb	X		X	X	
52	Amb	X		X	X	
53	Amb	X		X	X	
54	-65°F	X		X	X	
55	Amb	X		X	X	
56	Amb	X		X	X	
57	Amb	X		X	X	
58	Amb	X		X	X	
59	Amb	X		X	X	
60	Amb	X		X	X	
61	Amb	X	X	X	X	
62	Amb	X	X	X	X	
63	Amb	X	X	X	X	
64	Amb	X	X	X	X	
66	-65°F	X	X	X	X	
74	Amb	X	X	X	X	
75	Amb	X	X	X	X	
76	+160°F	X	X	X	X	
77	+160°F	X	X	X	X	
78	-65°F	X	X	X	X	
79	Amb	X	X	X	X	
80	-65°F	X	X	X	X	
82	Amb	X		X		X
83	Amb	X		X		X
84	-65°F	X		X		X
85	-65°F	X		X		X
86	-65°F	X		X		X
87	+160°F	X		X		X
88	+160°F	X		X		X
89	+160°F	X		X		X

TYPICAL -65°F STARTER OPERATING CHARACTERISTICS
(HYDRAZINE MODE)

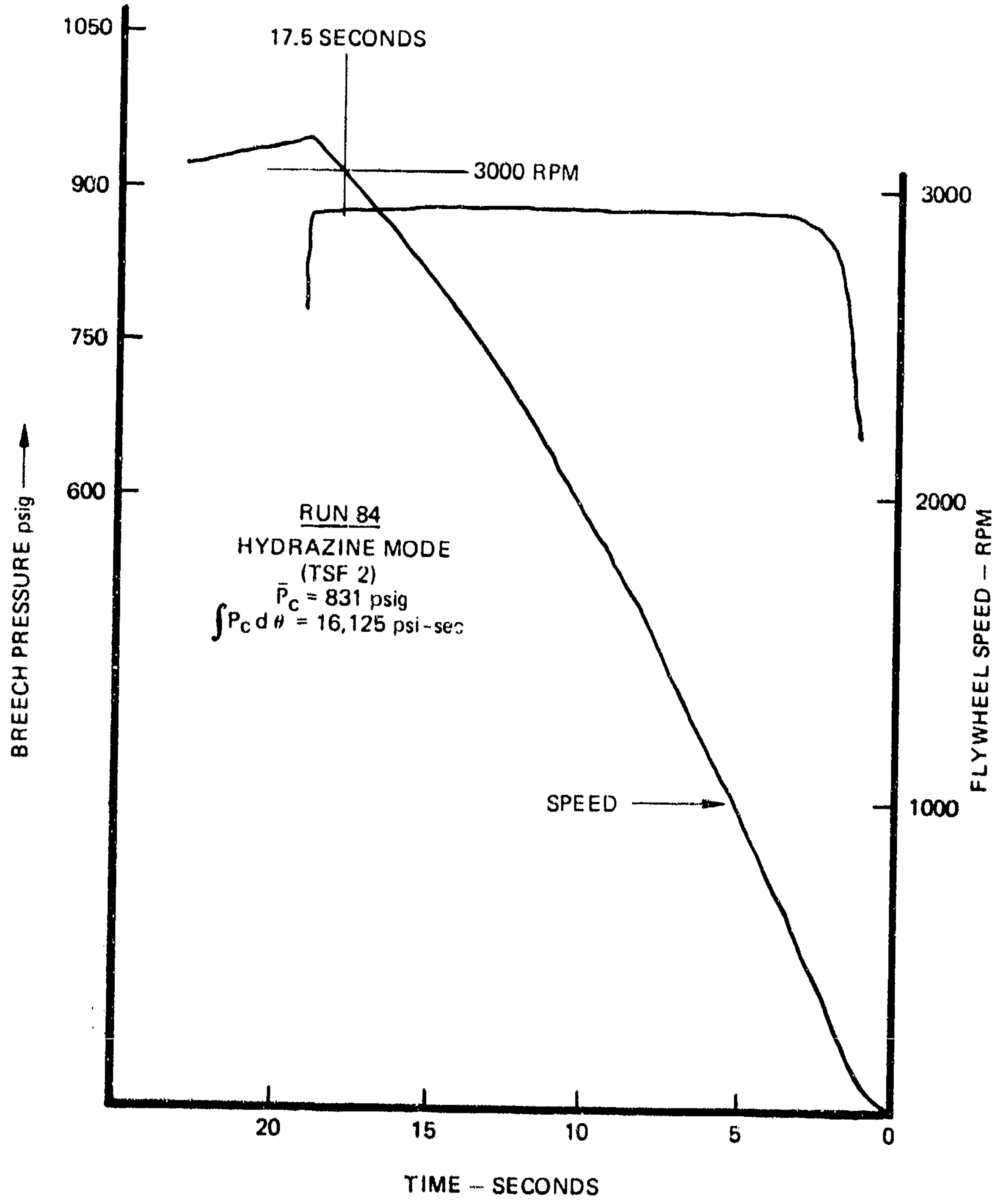
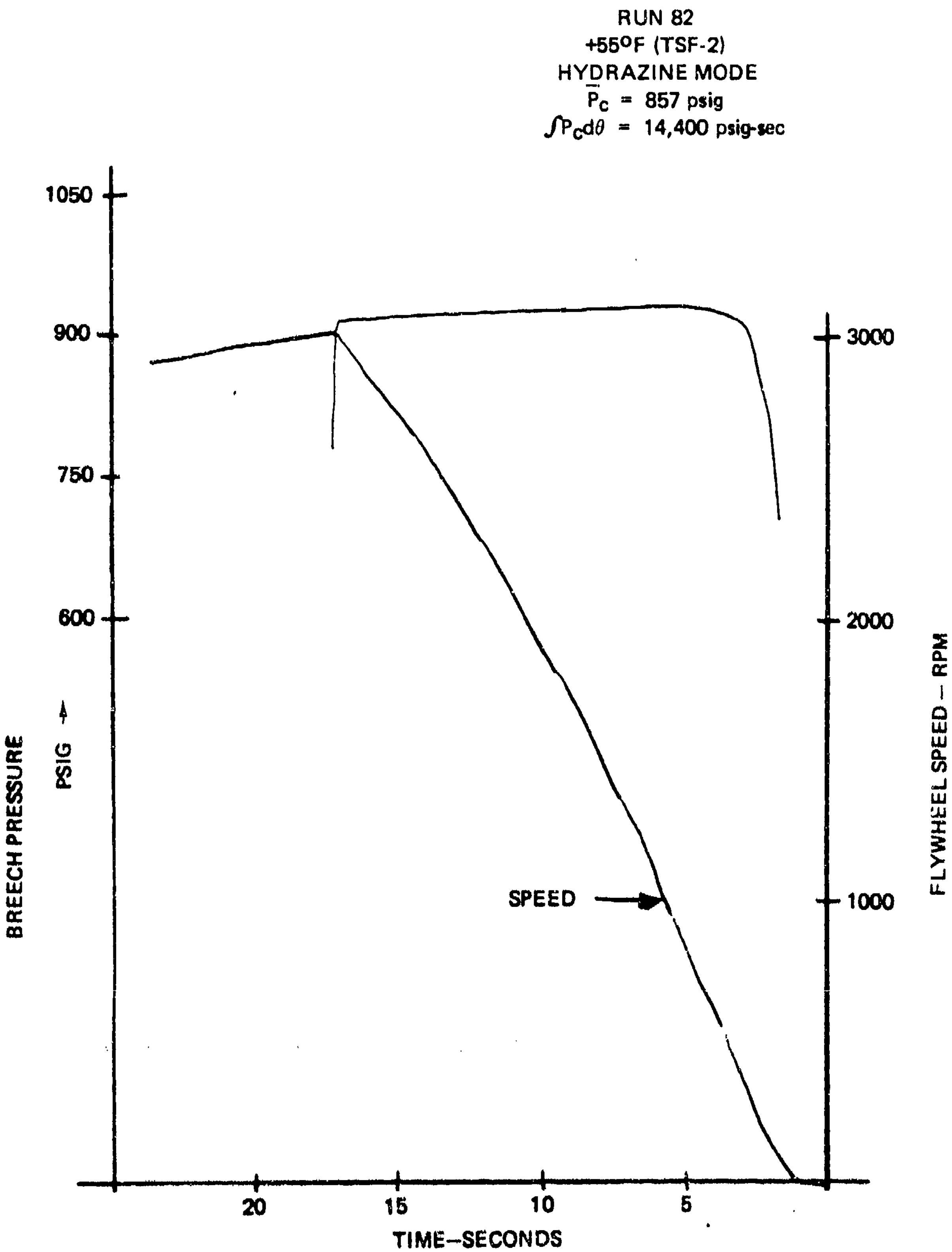


Figure 51

STARTER PERFORMANCE HYDRAZINE MODE



STARTER PERFORMANCE HYDRAZINE MODE

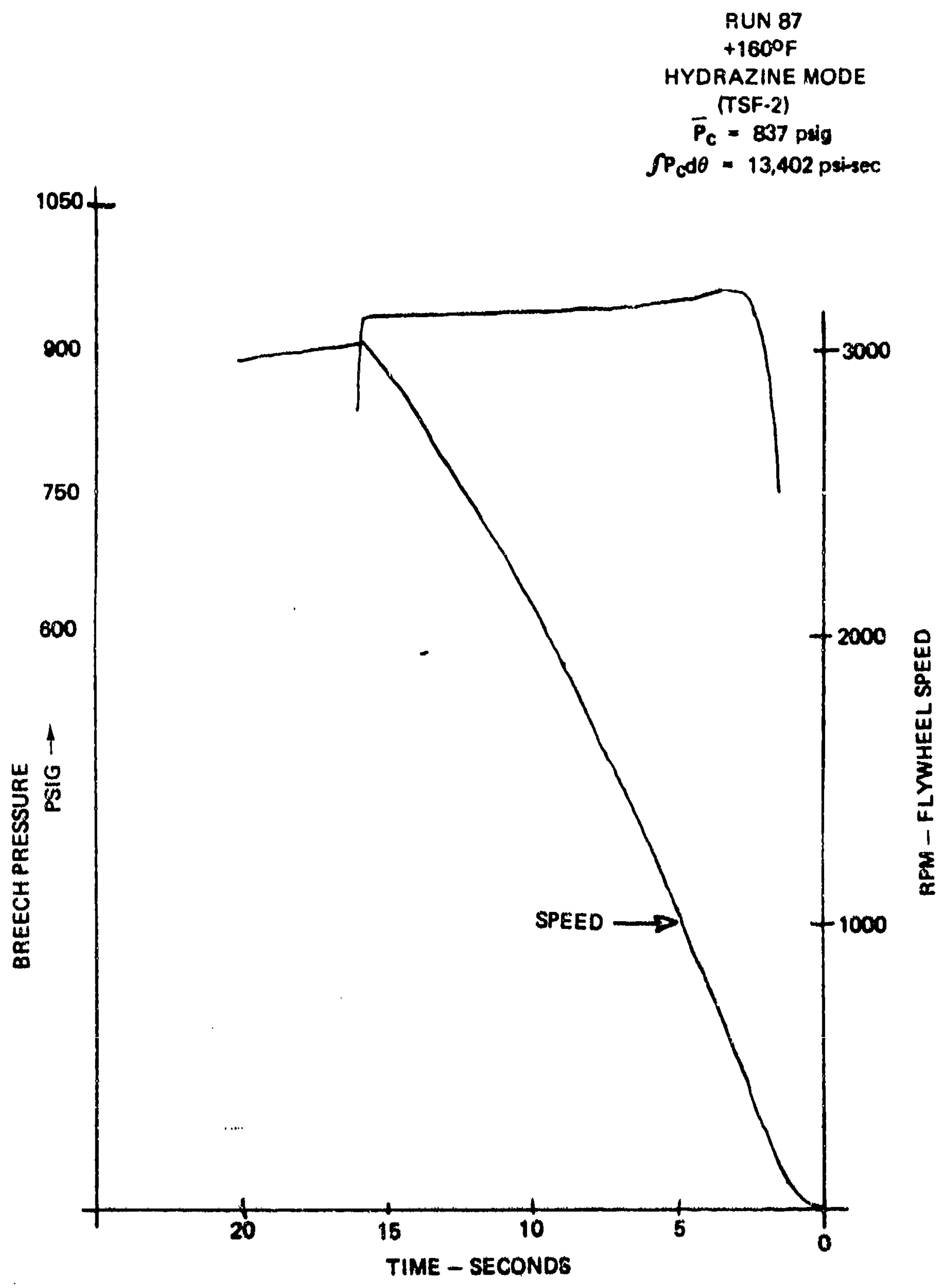
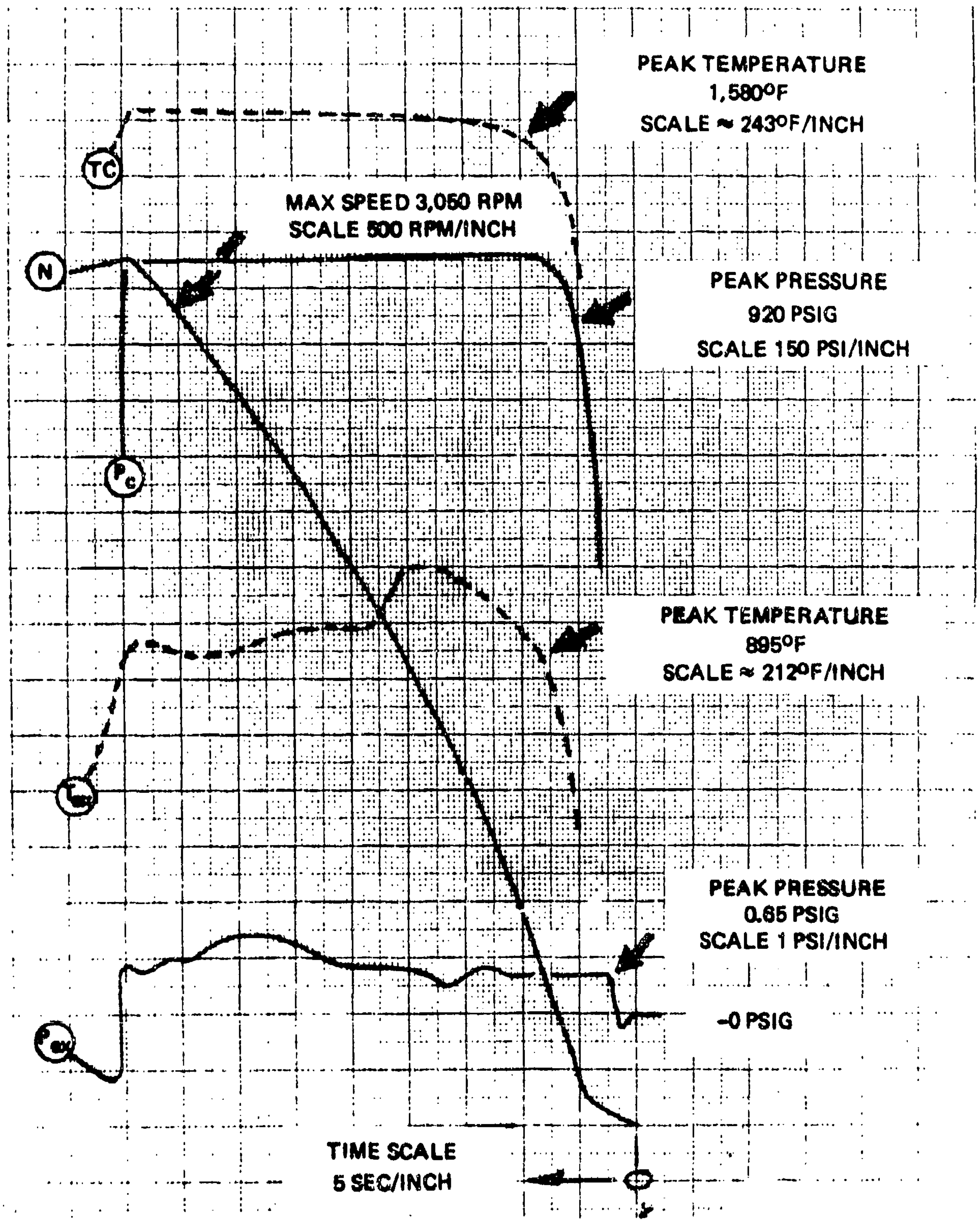


Figure 53

TEST DATA – RUN NO. 62



this quantity of fuel would be 181 in.^{3} at the minimum fuel density condition, which occurs at the +160°F soak temperature. The remaining 44 in.^{3} of breech volume would then be available for the hot gas pressurization subsystem that would be used to pressurize and expel the fuel from the fuel cartridge.

Hydrazine starter fuel consumption testing was subsequently conducted with both candidate fuel mixes (TSF-1 and TSF-2) over the required operating temperature extremes of -65 to +160°F. The results from these tests are summarized in Table 11 and discussed below.

3.4.2.4.1.1 TSF-1 Fuel Consumption

The first hydrazine-fueled starter test, run 49, required 7.86 lbm of fuel to duplicate the "cartridge-mode" starter performance at ambient temperature soak conditions. Run 49 chamber pressure data indicated that the starter relief valve had opened during the test, bypassing a portion of the hot gas around the turbine nozzles, effectively increasing the fuel consumption above the minimum obtainable value. The starter relief valve spring pressure was increased to prevent the valve from opening, and the test was repeated. The fuel consumption was reduced from 7.86 to 7.38 lbm (run 50).

Runs 51 and 52 were conducted at fuel supply pressures 100 psi lower and higher than the nominal value of 1,250 psi to determine the probable optimum operating pressure requirement. Both tests resulted in higher fuel consumption that that of run 50. Within the accuracy of the test results, it appears that 1,250 psi is near optimum for the fuel supply pressure at ambient test conditions.

Run 53 was a repeat of run 50 to gain insight into the repeatability of starter performance and fuel consumption at ambient test conditions. Fuel consumption repeatability between runs 50 and 53 was within 2.7 percent.

Run 54 was the first hydrazine-fueled starter test at -65°F soak conditions. The pressure drop through the breadboard fuel supply system was found to be excessive, resulting in a low value of breech gas pressure (P_c). A fuel consumption of 8.69 lbm was noted.

After run 55, the starter relief valve was further modified in an attempt to reduce fuel consumption. During starter overhaul, the starter relief valve is adjusted in such a way as to keep the valve pintle from seating (≈0.005- to 0.007-inch gap) at ambient temperature. The relief valve was subsequently modified to assure that the pintle did seat to prevent any loss of breech gas.

The average fuel consumption during the next 10 ambient temperature starter tests was 7.30 lbm/start. Fuel consumption at -65°F (runs 54 and 66) averaged 8.69 lbm, and +160°F fuel consumption averaged 6.64 lbm (runs 66 and 67).

The fuel consumption of 8.69 lbm as measured during the -65°F tests (runs 54 and 66) was thought to be greater than the minimal obtainable value due to operating the gas generator at a low pressure

Table 11
HYDRAZINE STARTER FUEL CONSUMPTION SUMMARY

1	2	3	4	5	6	7	8
Run No.	Max Flywheel Speed (rpm)	Time to Max Flywheel Speed (sec)	Test Condition	Total Fuel Consumed (lbm)	Max Speed (Cartridge Mode) N_c(1)	Time to N_c (sec)	Net Fuel Consumption to Flywheel Speed N_c (lbm)
49	3,190	19.9	Amb	8.93	2,960	17.5	7.86
50	3,100	18.5	Amb	7.98	2,960	17.1	7.38
51	3,000	19.0	Amb	8.06	2,960	18.6	7.90
52	2,980	16.0	Amb	7.78	2,960	15.75	7.74
53	3,020	17.2	Amb	7.78	2,960	16.8	7.58
54	3,120	22.5	-65°F	8.89	3,070	22.0	8.69
55	3,010	17.0	Amb	7.62	2,960	16.8	7.54
56	3,040	17.7	Amb	7.90	2,960	17.2	7.66
57	3,030	16.8	Amb	7.62	2,960	16.3	7.38
58	3,040	16.9	Amb	7.46	2,960	16.5	7.27
59	3,020	17.0	Amb	7.46	2,960	16.7	7.30
60	3,050	17.4	Amb	7.62	2,960	16.6	7.27
61	No fuel consumption data						
62	3,060	18.0	Amb	7.30	2,960	17.1	6.91
63	3,000	17.5	Amb	7.70	2,960	17.0	7.46
64	3,020	17.7	Amb	7.62	2,960	17.2	7.38
66	3,150	24.0	-65°F	9.09	3,070	23.0	8.69
74	3,020	18.7	Amb	8.57	2,960	18.2	8.34(2)
75	3,000	16.6	Amb	7.38	2,960	16.2	7.19
76	3,040	16.7	+160°F	7.62	2,770	14.7	6.71
77	2,980	16.3	+160°F	7.30	2,770	14.7	6.59
78	3,050	17.4	-65°F	7.98	3,070	17.6	8.06
79	3,030	16.8	Amb	7.46	2,960	16.2	7.19
80	3,140	18.3	-65°F	8.22	3,070	17.7	7.94
TSF-1 fuel mix							
TSF-2 fuel mix							
82	3,000	17.0	Amb	7.02	2,960	16.8	6.95
83	3,020	16.5	Amb	6.95	2,960	16.0	6.71
84	3,160	19.0	-65°F	7.90	3,070	18.3	7.62
85	3,070	20.5	-65°F	8.93	3,070	20.5	8.93(2)
86	3,070	17.0	-65°F	7.78	3,070	17.0	7.78
87	3,020	15.8	+160°F	6.79	2,770	14.0	5.92
88	No fuel consumption data						(3)
89	3,050	18.0	+160°F	–	2,770	14.1	(3)

Notes:

(1) Cartridge mode performance from Figure x-xx, paragraph x.x.x.x

(2) Starter performance anomaly – flywheel acceleration rate low

(3) Test valve failure – propellant control valve did not close

(P_c) because of the excess pressure drop in the breadboard fuel supply system. The -65°F fuel consumption tests were repeated (runs 78 and 80) with higher fuel supply pressure to verify this assumption. The fuel consumed at -65°F decreased as expected to an average value of 8.0 lbm/start.

3.4.2.4.1.2 TSF-2 Fuel Consumption Testing

The worst-case fuel consumption per start cycle with the more energetic fuel mix TSF-2 at -65°F soak conditions was determined to be 7.7 lbm (runs 84 and 86), a reduction of approximately 3.7 percent as compared to the TSF-1 fuel consumption.

3.4.2.4.2 Discussion of Test Results

The fuel consumption test results are plotted in Figure 55. Referring to Figure 55, the average fuel consumption per start cycle for both fuel mixes has been plotted in terms of fuel volume required per start cycle as a function of ambient soak temperature prior to starter operation.

The least energetic fuel mix (TSF-1), requires 192.5 $in.^3$ of fuel at the worst-case fuel consumption condition of -65°F. Fuel density change with ambient temperature excursions would require a minimum fuel cartridge volume of 211 $in.^3$ to accommodate fuel expansion at the upper operating temperature limit of +160°F (dashed line). It should be noted that there is considerable excess fuel available at all temperatures above the -65°F soak condition.

The most energetic candidate fuel mix, TSF-2, requires 185.5 $in.^3$ of fuel at the -65°F start condition and a minimum of 203 $in.^3$ of fuel cartridge volume to accommodate the fuel expansion at +160°F operating conditions.

Thus even with the most energetic fuel mix (TSF-2), the total fuel required to provide equivalent "cartridge-mode" starter performance at -65°F test conditions (203 $in.^3$) could not be packaged within the 181 $in.^3$ volume allotted to the fuel cartridge in the flight concept preliminary design of RRC drawing SK 5585, Rev. A. Therefore, it was decided at this time that a new flight concept configuration would be required to provide the additional necessary volume for the TSF-2 hydrazine mix.

Two alternate design solutions were available to provide the additional fuel cartridge space in the flight concept design.

a. Redesign the hydrazine-fueled pressurization subsystem to reduce its volume by (203-181) 22 $in.^3$.

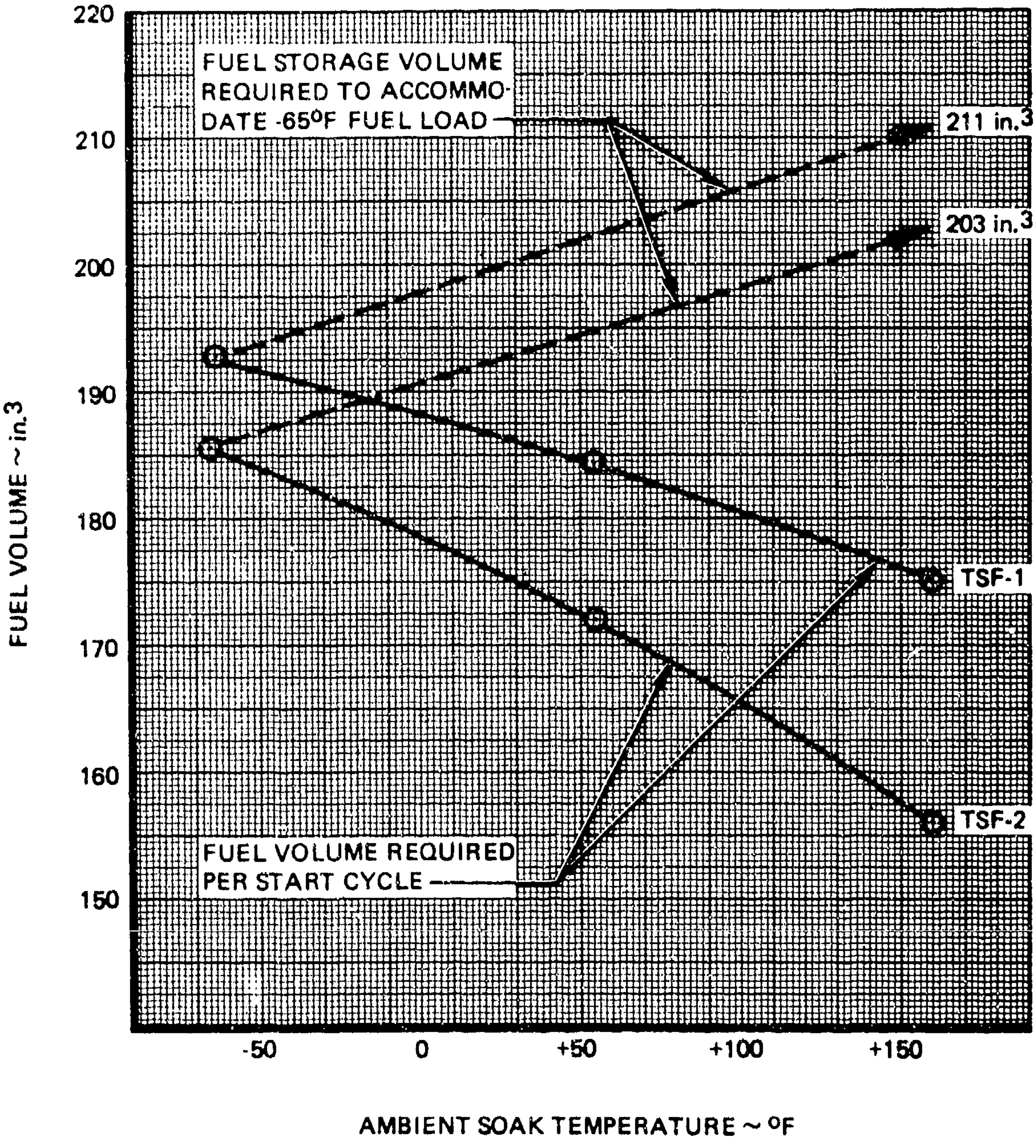
b. Or revise the pressurization subsystem to a more compact, solid propellant-fueled subsystem.

The second approach was felt to be the most practical approach and is discussed in detail in paragraph 3.5.

3.4.2.5 Limited Life Demonstration

There was a contractual requirement to demonstrate a limited life capability for the flight concept gas generator of 20 full-power starter operating cycles. The 20-cycle limited life demonstration was to include at least two cycles at each of the temperature extremes of -65 and +160°F.

HYDRAZINE STARTER FUEL CONSUMPTION REQUIREMENTS



Thirty-two full-power gas generator operating cycles were demonstrated; 7 at -65, 5 at +160, and 20 at ambient temperature. No detectable degradation in the performance of the unit was noted.

3.4.3 Exhaust Gas Sampling and Analysis

The exhaust gas from the hydrazine-fueled starter was sampled, near the turbine exit plane, at -65, ambient, and +160°F soak conditions and analyzed for nitrous oxides, unreacted fuel, and percent by volume of ammonia and water during starter operation with the TSF-1 fuel mix.

Neither nitrous oxides nor unreacted fuel were detected above the experimental threshold level of 0.1 parts per million. The time-averaged exhaust gas composition includes nitrogen, hydrogen, ammonia, and water as described by the following reaction equation:

$$N_2H_4 + 0.118\ N_2H_5NO_3 + 0.563\ H_2O \longrightarrow x\,(1.941)\ H_2$$

$$+\ 0.917\ H_2O + (0.646X + 0.531)\ N_2 + (1 - X)\,(1.294)\ NH_3$$

where X is a factor that accounts for the amount of ammonia dissociated into nitrogen and hydrogen.

The time-averaged value of X as determined by the exhaust gas analysis at -65, ambient, and +160°F soak conditions is as follows:

$\bar{X}$ = 0.338 at -65°F

$\bar{X}$ = 0.518 at ambient

$\bar{X}$ = 0.583 at +160°F

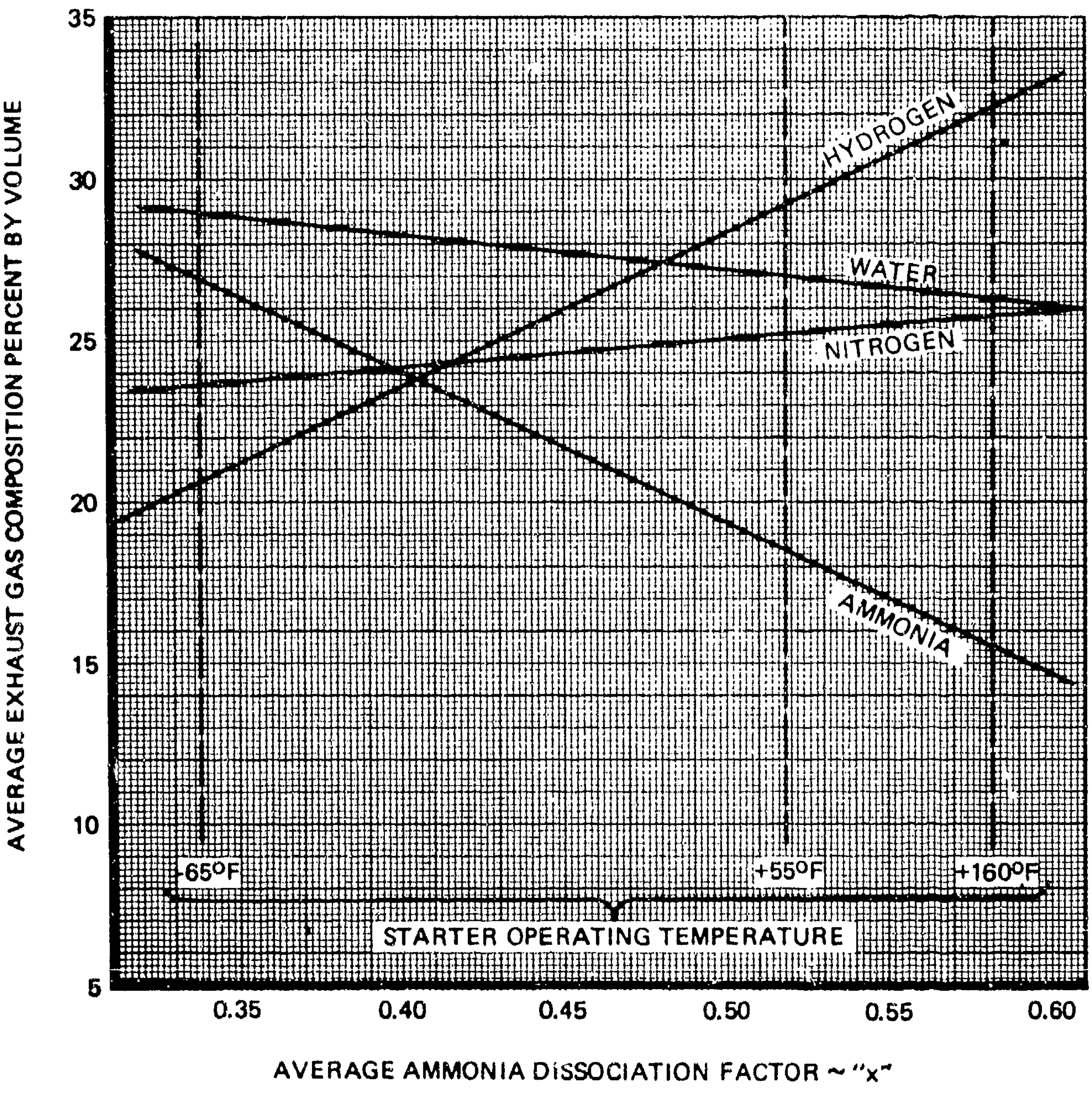
The time-averaged value of the ammonia dissociation factor can be used with the foregoing reaction equation to determine the average starter exhaust gas composition during starter operation, as shown in Figure 56.

3.4.3.1 Gas Sampling Apparatus

A sketch of the hydrazine-fueled starter exhaust gas sampling apparatus is shown in Figure 57. The exhaust gas was extracted from the starter exhaust duct through a 3/8-inch stainless steel Pitot tube located approximately 2 inches downstream of the starter turbine wheel. The exhaust gas samples were collected in two stainless steel sample cylinders. A 75-cc cylinder was used to sample for nitrous oxides and unreacted fuel, and a 13.9-liter cylinder was used to collect a large gas sample for composition analysis. The sample cylinders were evacuated with a small mechanical vacuum pump prior to each sampling test. Exhaust gas flow into the sample cylinders was effected by energizing a normally closed electric solenoid valve.

The Pitot tube (external to the exhaust pipe) sample valve and the hand valves on the sample inlet side of both sample cylinders were heated electrically to at least 200°F prior to operating the starter to prevent condensation of water and/or ammonia upstream of the sample cylinders. The gas sample pressure (P_s) and temperature (T_s) were monitored and recorded continuously.

AVERAGE STARTER EXHAUST GAS COMPOSITION
(TSF-1 FUEL MIX)



EXHAUST GAS SAMPLING APPARATUS

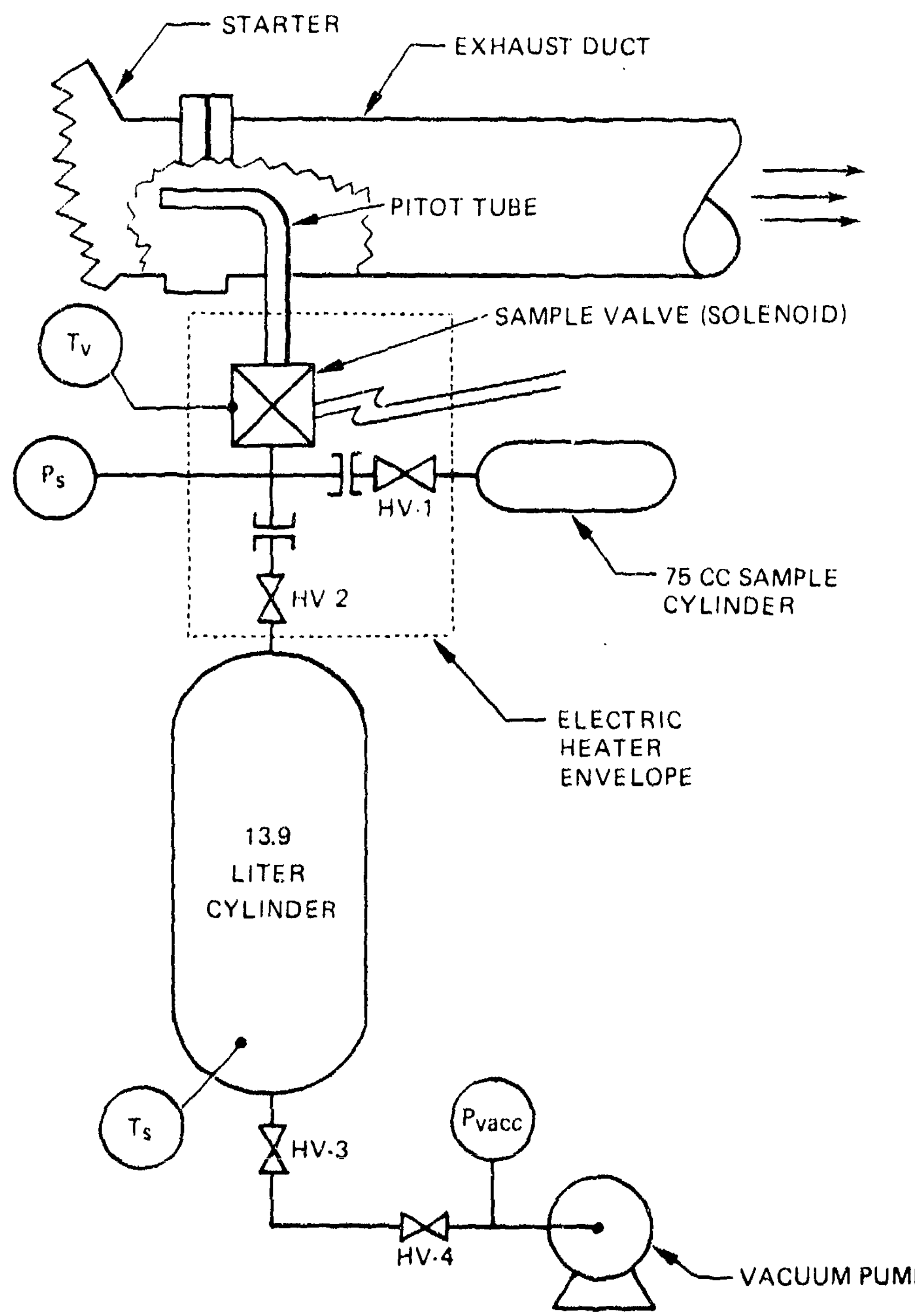


Figure 57

3.4.3.2 Gas Sampling Procedure

Prior to each gas sampling test, the sample cylinders were flushed with distilled water, rinsed with isopropyl alcohol, evacuated, and oven dried at 100°C. The sample cylinders were then installed as shown in Figure 57. Hand valves (HV-1, HV-2, HV-3, HV-4) were opened, and the cylinders were evacuated with the vacuum pump. The electric heater was energized and operated continuously until a temperature of at least 200°F was noted on the body of the sample valve. Hand valves HV-3 and HV-4 were then shut, and the pressure in the sample cylinders (P_S) was monitored to assure that there were no leaks in the sample system.

The starter was then installed, and the firing countdown was initiated. The sample valve was opened 0.2 to 0.4 second after the main fuel control valve was energized to initiate the starter spin-up. The sample valve was closed when the starter speed reached a value of approximately 50 rpm below the maximum programmed value.

Sample pressure and temperature (P_S and T_S) were then noted, and the sample cylinders were isolated by closing hand valves HV-1 and HV-2. The 75-cc sample cylinder was then removed and routed to the chemical laboratory for immediate analysis for nitrous oxides and unreacted fuel. The 13.9-liter sample cylinder was subsequently removed and routed to the chemical laboratory for exhaust gas composition analysis. The final pressure in the sample cylinders was typically noted to be slightly subambient (12 to 14 psia). Sample temperature (T_S) typically peaked at 10 to 15°F above local ambient temperature.

3.4.3.3 Gas Analysis Technique

The analysis techniques for the hydrazine-fueled starter exhaust gas sampling task are presented and discussed as follows.

3.4.3.3.1 Analysis for Gas Composition

The theoretical exhaust gas composition for the catalytic decomposition of the TSF-1 fuel mix are nitrogen, hydrogen, ammonia, and water in quantites related to the degree of completion of the endothermic dissociation of ammonia per the following reaction equation.

$$N_2H_4 + 0.118\ N_2H_5NO_3 + 0.563\ H_2O \longrightarrow (X)\ (1.941)\ H_2$$

$$+ (0.917)\ H_2O + (1 - X)\ (1.294)\ NH_3 + (0.646X + 0.531)\ N_2$$

where (X) is the fraction of ammonia dissociated.

In the absence of any secondary reactions which may form nitric oxides and in the absence of any unreacted fuel in the exhaust products, the ammonia dissociation factor "X" may be determined from the ratio of the weights of water and ammonia present in a given sample of the exhaust products using the following relationship derived from the reaction evaluation.

$$X = 1 - \frac{(0.917)\,H_2O}{(1.294)(NH_3)} \cdot \frac{Wt\,(NH_3)}{Wt\,(H_2O)}$$

The ammonia dissociation factor (X) was determined experimentally with the apparatus shown in Figure 58. Referring to Figure 58, the 13.9-liter gas sample cylinder was installed in an oven and heated to 100°C. Heating raised the gas pressure above local ambient and assured that the water and ammonia constituents in the gas sample were in the gaseous phase.

The hot gas sample was then allowed to flow slowly through the test apparatus. Water was removed from the gas sample in the first flask, which contained hygroscopic Ascarite (N_AOH on alumina carrier). The water free gas sample then passed into the second flask where the ammonia was absorbed in a H_2SO_4 solution.

The weight of water collected was determined by weighing the Ascarite flask before and after. The amount of ammonia collected in the second flask was determined by back titrating the contents of the second flask.

3.4.3.3.2 Analysis for NO_x and Unreacted Fuel

The 75-cc sample cylinder was pressurized to approximately 30 psig with gaseous helium, and the resultant exhaust gas/helium mixture was analyzed for NO_x and unreacted fuel by colormetric techniques.

The principle of the method used for NO_x analysis is the diazotization of sulfanilic acid which couples with N-(1-napthyl) ethylene diamine to form a stable red dye. The method will measure nitric oxide if sufficient air is admitted to convert all nitric oxide to nitrogen dioxide.

The method involved the preparation of a 200-ml reagent solution containing 188 ml of sulfanilic acid solution*, 4 ml of the N (1-napthyl) ethylene diamine dihydrochloride solution**, and water.

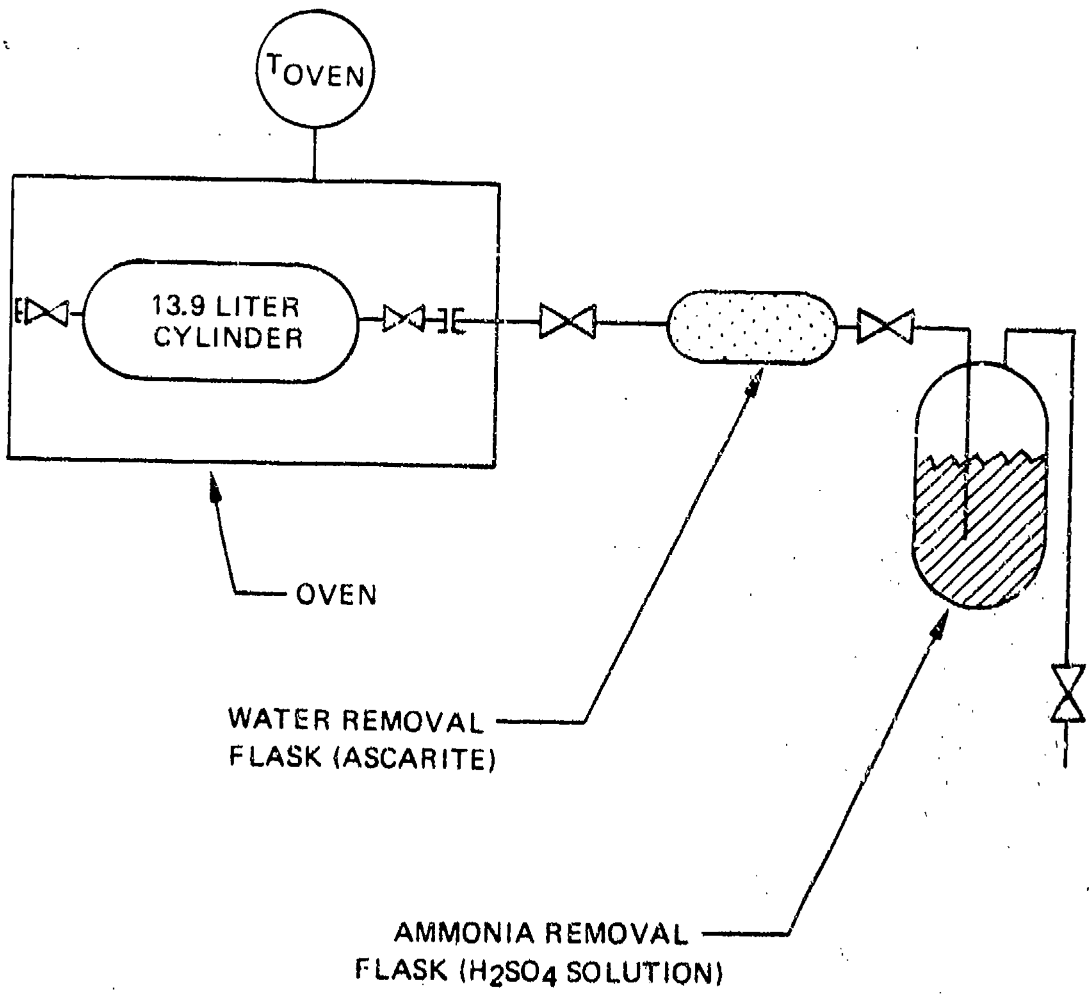
Twenty ml of the reagent solution was drawn into an all-glass syringe. A 22-gauge needle was attached, the syringe was inverted, and entrapped air was forced out of the syringe. With the syringe inverted, the needle was inserted through a septum on the sample cylinder and 80 ml of gas was allowed to enter the syringe. The needle was removed from the septum, and the pressure in the syringe was allowed to equalize with ambient pressure while maintaining the 80-ml gas volume. Twenty ml of ambient air were then drawn into the syringe and the needle was capped. The syringe was then shaken intermittently for 20 minutes. After rinsing a 1-cm pyrex cell with the reagent solution, the absorbance of the syringe sample was measured at 550 μm using a Hitachi-Perkin-Elmer double-beam spectrophotometer, using a reagent blank as reference.

---

*10 grams sulfanilic acid dissolved in 800 ml distilled water plug 140 ml glacial acetic acid.

**0.2 gram N (1-napthyl) ethylene diamine dihydrochloride in 100 ml distilled water.

EXHAUST GAS COMPOSITION ANALYSIS APPARATUS



NO_X determination was quantitized by comparing the results with calibration curves prepared from 1, 2, and 3 ml of a standard sodium nitrite solution*** mixed in 100-ml volumetric flasks with 20-ml reagent solution and filled to the mark with distilled water, yielding absorbance equivalent to 50, 100, and 150 ppm NO_2 in the 80-ml gas sample.

The analysis for unreacted fuel was also done by colormetric technique using a reagent solution of paradimethyl aminobenzadehyde.

The procedure involved loading of 10 ml of the PDAB solution into the syringe, adding 80 ml of the exhaust gas, capping the syringe, and shaking intermittently for 10 minutes. The liquid from the syringe was then injected into a 25-ml flask and filled to the mark with 1.0 M HCl. The absorbance was measured at 458 μm and the quantity of N_2H_4 was determined from reference calibration curves.

3.4.4 Exhaust Gas Composition – TSF-2

As noted, the foregoing exhaust gas sampling and analysis was conducted during starter operation with the TSF-1 fuel blend.

Since there is very little difference in the composition of the TSF-1 and TSF-2 fuel blends, the exhaust gas composition for the TSF-2 fuel blend can be estimated with a high confidence level per the following.

The reaction equation for the TSF-2 fuel blend is:

$$N_2H_4 + 0.145\ N_2H_5NO_3 + 0.521\ H_2O \longrightarrow (1 - X)(1.285)\ NH_3$$
$$+ X(1.928)\ H_2 + (0.642X + 0.575)\ N_2 + 0.956\ H_2O$$

where X is the ammonia dissociation factor.

The experimentally determined values for the average ammonia dissociation factor based on time-averaged gas temperature measurements taken during starter testing with TSF-2 fuel are:

$\bar{X}$ = 0.367 at -65°F

$\bar{X}$ = 0.556 at ambient

$\bar{X}$ = 0.643 at +160°F

Thus, the average composition of the TSF-2 fueled starter exhaust products can be estimated by substituting the average ammonia dissociation factors above in the reaction equation for the TSF-2 fuel mix.

***2.03 grams dry sodium nitrite diluted to 1 liter with distilled water.

The time-averaged value and the steady-state value of the ammonia dissociation factor are summarized in Figure 59 for starter operation with TSF-1 and TSF-2 fuel mixes, as a function of ambient soak temperature. Figure 60 depicts the thermochemical reaction temperature for both fuel blends as a function of the instantaneous ammonia dissociation factor.

3.5 PRESSURIZATION SUBSYSTEM TESTING

The initial flight concept versions of the hydrazine-fueled starter -- RRC drawing SK 5585 and RRC drawing SK 5585, Rev. A -- envisioned hot gas pressurization of the fuel cartridge/breech ullage using a pressure-regulated, hydrazine-fueled, gas generating subsystem.

Phase II hydrazine starter fuel consumption testing subsequently eliminated the hydrazine-fueled pressurization subsystem as a viable candidate for the starter application because of the requirement for increasing the quantity of fuel that would have to be stored in the breech envelope to duplicate the "cartridge-mode" starter performance.

The final flight concept version of the hydrazine-fueled starter, RRC drawing SK 5762, Rev. A, is configured with a solid-propellant-fueled pressurization subsystem. This approach minimizes the space required for the pressurization system and affords the maximum possible space available for the liquid fuel cartridge.

The solid propellant pressurization concept and the results of the breadboard solid propellant pressurization subsystem test program are discussed below.

3.5.1 Solid Propellant Pressurization Concept

The basic solid propellant pressurization concept is simple in principle and involves matching the rate of gas generated by the burning solid propellant cartridge ($\dot{V}_s$) to the rate of liquid fuel consumed by the starter ($\dot{V}_p$) at the required starter fuel supply pressure (P_f).

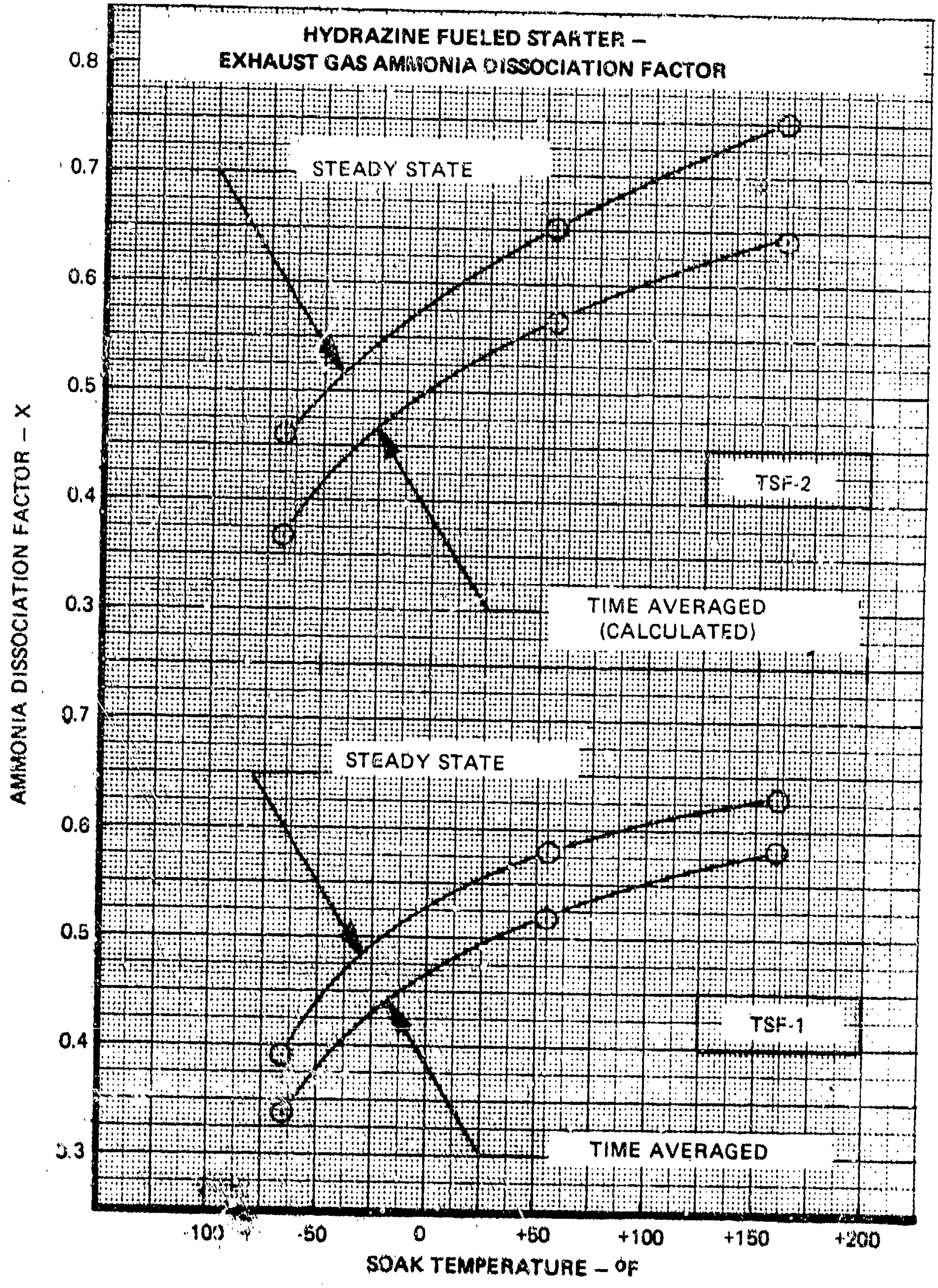
$$(\dot{V}_s = \dot{V}_p)_{P_f} \tag{1}$$

The rate of gas generated by the solid propellant cartridge can be stated

$$\dot{V}_s = \frac{\dot{W}_s \, R \, T_s}{P_f \, M_s} \tag{2}$$

where:

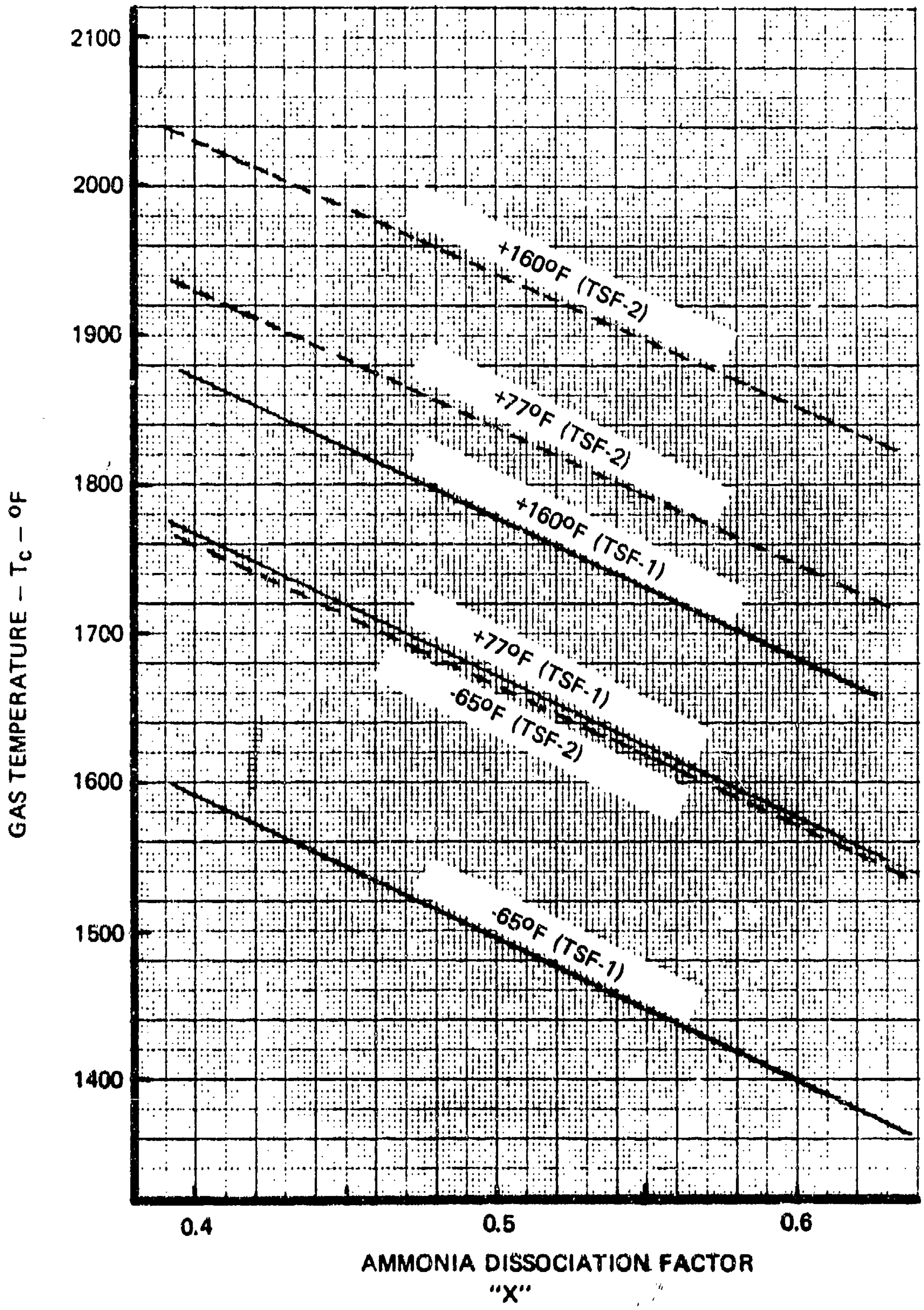
$\dot{W}_s$	=	Mass rate of gas generated, lbm/sec
R	=	Universal gas constant, ft lb/lb mole ^{o}F
T_s	=	Temperature of gas generated
P_f	=	Fuel supply pressure = burning pressure, lbf/ft^2
M_s	=	Molecular weight of the solid propellant exhaust products, lbm/lb mole



HYDRAZINE FUELED STARTER –
EXHAUST GAS AMMONIA DISSOCIATION FACTOR
AMMONIA DISSOCIATION FACTOR – X
0.8
0.7
0.6
0.5
0.4
0.3
0.7
0.6
0.5
0.4
0.3
STEADY STATE
TSF-2
TIME AVERAGED
(CALCULATED)
STEADY STATE
TSF-1
TIME AVERAGED
-100
-50
0
+50
+100
+150
+200
SOAK TEMPERATURE – °F

Figure 50

THERMOCHEMICAL REACTION TEMPERATURE



The required burning surface area (A_B) for the solid propellant cartridge can be calculated if the propellant burning rate (r) and the propellant density (φ_S) ar. .nown.

$$A_B = \frac{\dot{W}_S}{r\,\varphi_S} \tag{3}$$

For the starter application, the solid propellant pressurization cartridge would ideally exhibit a neutral burning characteristic (constant pressure burning). Neutral burning can be obtained with a cartridge that burns on one end. The diameter of the cartridge (D_B) can be determined from the burning area (Equation 3), and the length of the cartridge (L) can be determined from the burn rate (r) and the required starter operating time (Θ) as follows:

$$D_B = \sqrt{\frac{A_B}{\pi/4}} \tag{4}$$

$$L = \frac{\Theta}{r} \tag{5}$$

Thus, assuming that the solid propellant cartridge is sized for one operating condition, the cartridge sizing is straightforward if the effective gas composition (M_S) and gas temperature (T_S) are known.

The actual sizing of the solid propellant cartridge for the hydrazine-fueled starter application was done per the foregoing with the design point set at the minimum allowable fuel pressure at -65°F soak conditions. Certain assumptions were made regarding the composition of the exhaust gas (M_S) and the effective temperature of the exhaust gas (T_S) based on estimated heat transfer effects to the breech.

Extrapolating the gas generating characteristics of the solid propellant pressurization subsystem to ambient and +160°F operating conditions is an extremely difficult task. For instance, the pressure that the solid propellant gas generator would develop if the throat area (A*) were constant in the system can be expressed as

$$\frac{P_2}{P_1} = e^{\pi k(T_2 - T_1)}; \quad \frac{A_B}{A^*} = C \tag{6}$$

where:

πk	=	Temperature sensitivity of burning pressure at constant A_B/A^*
$(T_2 - T_1)$	=	Change in temperature

Thus, the pressure would tend to increase at ambient temperatures above the -65°F design point.

Additionally, the propellant burn rate at any temperature is a function of pressure

$$\frac{r_2}{r_1} = K(P)^n;\ T = C \tag{7}$$

where:

n = Burning rate pressure exponent

and even if the solid propellant pressurization subsystem were somehow pressure regulated, the burn rate would increase with temperature in accordance with

$$\frac{r_2}{r_1} = e^{\sigma P\,(T_2 - T_1)};\ P = C \tag{8}$$

where:

σP = $\pi_k(1 - n)$ = temperature sensitivity of burn rate at constant pressure

In the hydrazine starter application, A_B/A^* is not constant, heat transfer to the breech walls and fuel cartridge affects the temperature and molecular composition of the pressurization gas, there is no pressure regulator, and the unit must function over a broad temperature range.

Detailed analysis was conducted to predict the operating characteristics of the solid propellant pressurization subsystem over the complete -65 to +160°F operating range. Based on these analyses, the basic or conceptual operating characteristics of the flight system will be reviewed in the following subsection.

3.5.1.1 Solid Propellant Pressurization Subsystem Operating Characteristics

Figure 61 depicts the allowable fuel pressure limits, as a function of ambient temperature, for the hydrazine starter.

If the pressurizing propellant has a high value of π_k, then a cartridge that has been sized to satisfy the -65°F fuel supply requirements will function satisfactorily from -65°F to some intermediate temperature (point 1); operation at temperatures in excess of point 1 may result in mechanical failure, excess fuel consumption, or some other undesirable condition.

If a pressurizing propellant is selected with a low value of π_k, the starter could operate satisfactorily between the -65°F design point and the upper temperature limit (point 2).

Rocket Research Corporation conducted a propellant supplier survey to determine the availability of propellants with low values of π_k. The results of this survey indicated that there were no propellants available that would satisfy the -65°F to point 2 requirements shown on Figure 61. Several propellant suppliers have commercially available propellant with π_k values in the nominal 0.2 to 0.3 percent/°F range.

Π_k EFFECTS

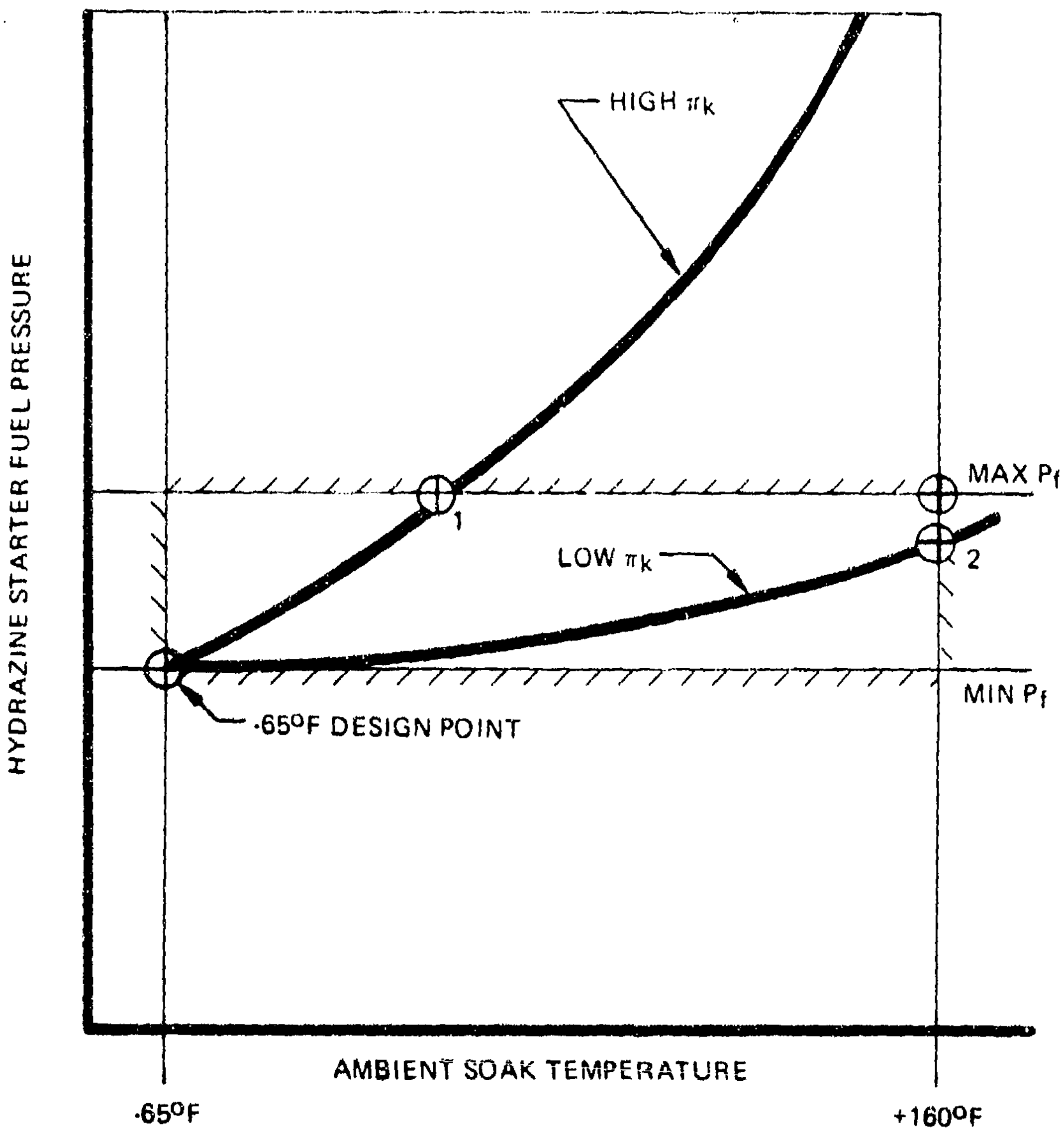


 Figure 61

Talley, a propellant supplier for the MXU4A/A cartridge used with the cartridge starter, provided test sample cartridges for the pressurization subsystem test program. This propellant, designated TAL 431MOD.076, has a π_k value of 0.22 percent/°F.

Rocket Research Corporation has developed a technique for using the Talley propellant that reduces the effect of higher than desired π_k. Figure 62 depicts the approach.

Referring to Figure 62, the solid propellant cartridge is designed to the minimum fuel pressure, -65°F operating point. This will allow satisfactory starter operation between -65°F and the intermediate temperature of point 1. At point 1, the ratio of burn area to effective throat area, A_B/A^*, is decreased by opening a bleed orifice and dumping a predetermined percentage of the gas being generated. This allows the pressure in the breech to be reduced (point 2) to the minimum allowable value, providing acceptable starter performance between -65°F and point 3.

Point 3 may lie to the left of the +160°F temperature line, within certain limits, and still allow acceptable starter performance at the +160 limit. There is excess fuel available at +160°F, and the starter pressure relief valve, which is located just upstream of the turbine nozzle block, can be set to relieve the excess gas generated by the hydrazine-fueled gas generator, if required.

3.5.2 Solid Propellant Pressurization Subsystem Test Results

Rocket Research Corporation procured 25 cartridges from Talley Industries of Arizona to evaluate the proposed solid propellant pressurization subsystem approach experimentally. The test apparatus, test program, and test results are described below.

3.5.2.1 Test Apparatus

A breadboard version of the proposed solid propellant pressurization subsystem and a liquid fuel expulsion device were fabricated to evaluate the pressurization subsystem concept at the component level, at -65, ambient, and +160°F soak conditions. The test apparatus is shown in Figures 63 through 65.

Figure 63 is a sketch of the gas generator/fuel expulsion device. The gas generating portion of the subsystem includes the breech assembly, solid propellant cartridge, and ignitor. Hot gas generated by the solid propellant cartridge is used to pressurize the piston in the aircraft type accumulator. Approximately 370 in.^{3} of fuel is contained in the space below the piston. A liquid flow control orifice is located in the discharge end of the accumulator. Fuel retention is accomplished with a 1,000-psi burst disc.

The solid propellant cartridge is an end burning configuration, 2.1 inches in diameter and 1.5 inches in length. The cartridge is inhibited on the cylindrical surface and one end. The propellant is a gum rubber/ammonium nitrate blend designated as TAL 431MOD.076 and is identical to that used in late model Talley MXU4A/A solid propellant cartridges for the cartridge starter application. The supplier's data sheet for this propellant blend is shown in Figure 66.

The ignitor is a RRC-developed device utilizing two electric matches and pelletized $BKNO_3$.

SOLID PROPELLANT PRESSURIZATION SUBSYSTEM BLEED TECHNIQUE

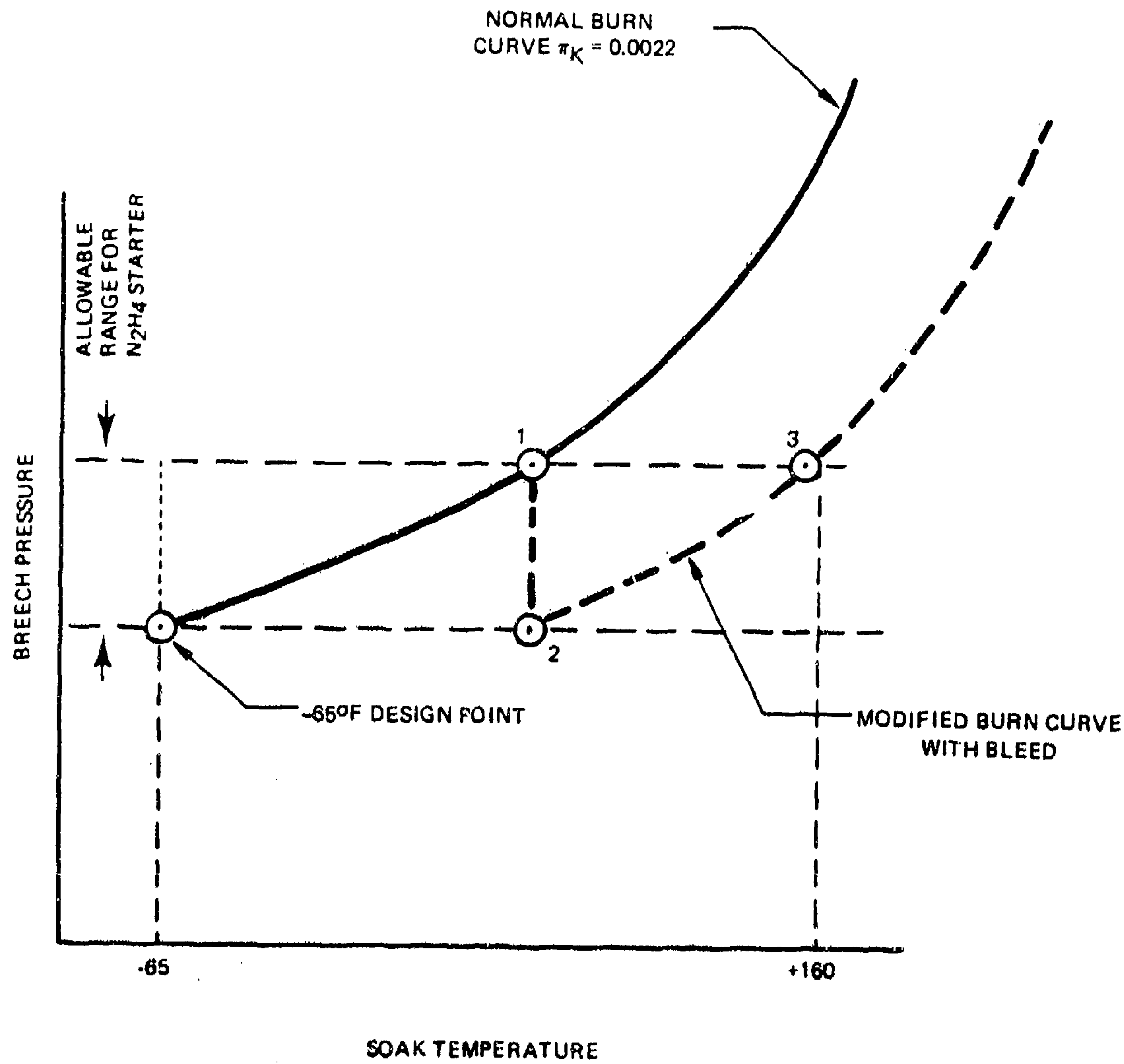


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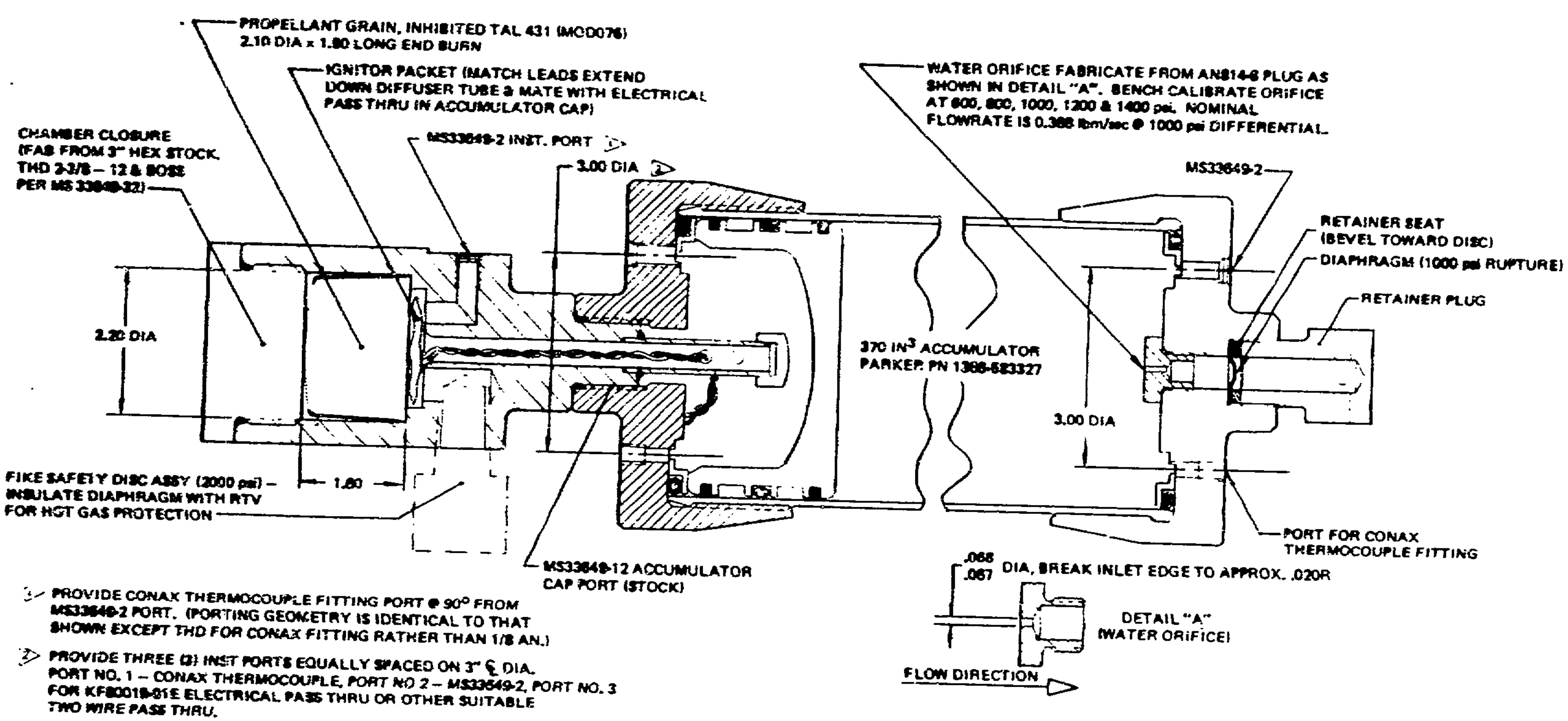
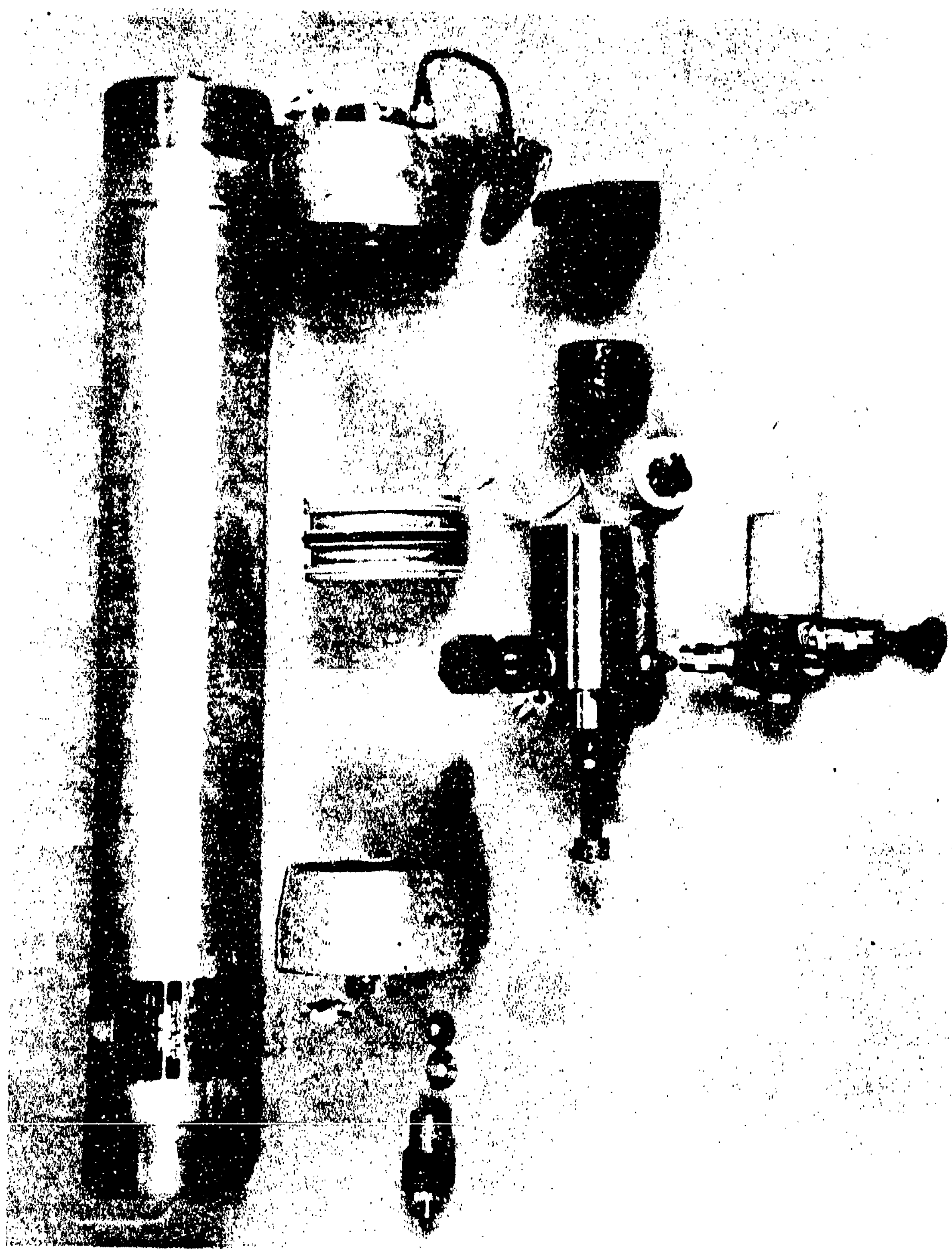
Figure 62

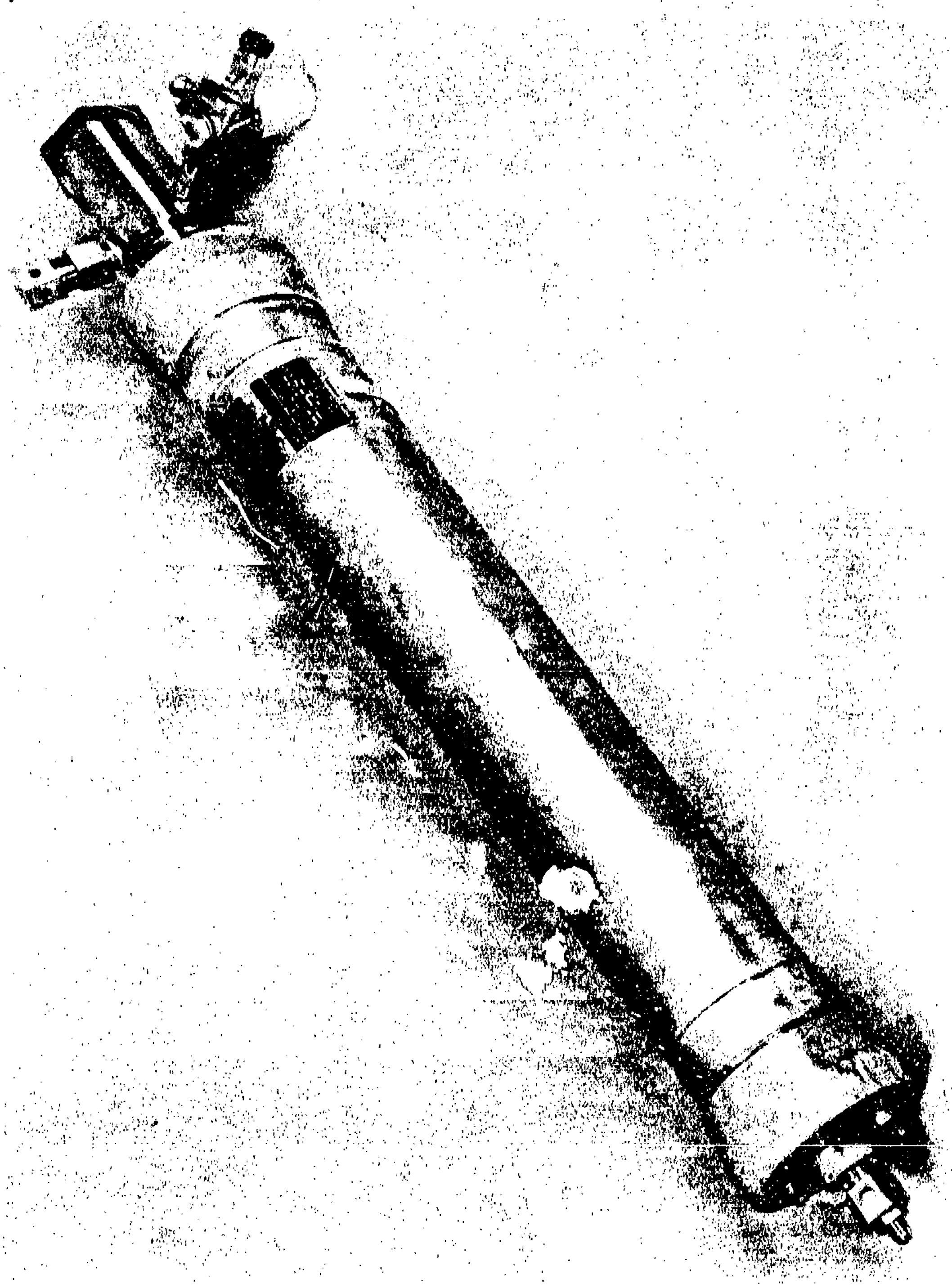
BREADBOARD SOLID PROPELLANT PRESSURIZATION SUBSYSTEM



BREADBOARD HYDRAZINE FUEL SUPPLY AND
SOLID PROPELLANT PRESSURIZATION SUBSYSTEM



BREADBOARD HYDRAZINE FUEL SUPPLY AND SOLID PROPELLANT PRESSURIZATION SUBSYSTEM



Talley Industries · Product Data Sheet

SOLID PROPELLANT DESIGNATION

TAL - 431 MOD 0.076

(Formerly 36-85-1)

Description: Gum Rubber/Ammonium Nitrate

BALLISTIC PROPERTIES:

Burning Rate Equation (80° F)	$r_b^{(i)} = 0.076\ (Pc/1000)^{0.46}$
Area Ratio Equation (80° F, calc)	$K_n = 2040\ (Pc/1000)^{0.54}$
Flame Temperature (°F, calc) ①	2132
Characteristic Exhaust Velocity (C*, ft/sec)	3919
Temperature Sensitivity (%/°F)	
Temp. Range -65° to +160° F	π pk = 0.22
Specific Impulse (1000 psia, lbf-sec/lbm, calc)	190.34
Molecular Weight, Gas (calc. avg.) ①	19.16
Ratio of Specific Heats (γ, calc)	1.269
Heat of Reaction (cal/gram)	860

Approximate Gas Composition (Mole %) ①

H_2	27.11	CH_4	0.04
H_2O	29.77	NH_3	0.03
CO	15.57	N_2S	0.17
CO_2	7.23		
N_2	20.08		

PHYSICAL PROPERTIES:

Temp (°F)	-65	80	160
Tensile Strength (psi, max)		60	
Elongation (% at max stress)		7	

Hardness (Shore "A", 80° F)	64
Density (lb/in³, 80° F)	.053

Autoignition:

> One hour at 350° F

ICC Classification	Flammable Solid

NOTES: ① Frozen flow calculations, chamber conditions.

(i) Burn rate range from 0.073 to 0.079 inches per second.

Published November, 1968

Figures 64 and 65 are photographs of the breadboard solid propellant pressurization subsystem apparatus. Figure 64 shows the individual subsystem components, and Figure 65 shows the complete assembly.

3.5.2.2 Test Setup

The fuel expulsion device and the solid propellant gas generator were installed in a 25 ft^3 environmental test chamber and instrumented shown in Figure 67.

Control requirements were limited to supplying 28-volt DC power to fire the ignitor and power to open the solenoid valve for hot gas bleed when used.

Three pressures were monitored with strain gauge transducers:

P_c	–	Breech chamber pressure in the gas generator
P_U	–	Accumulator pressure on gas side of piston
P_{TK}	–	Accumulator pressure on liquid side of piston

Four temperatures were measured with chromel alumel thermocouples:

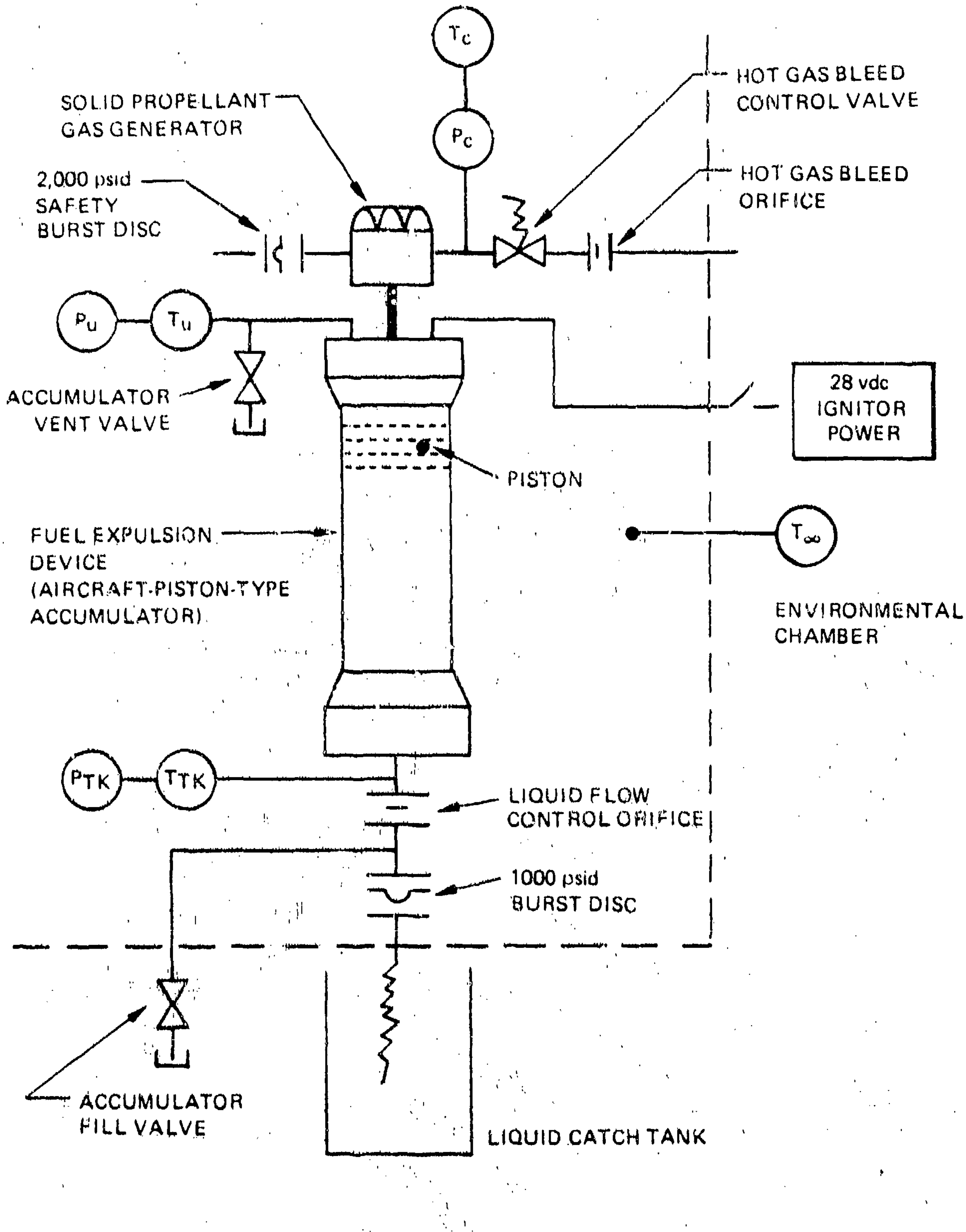
T_c	–	Gas temperature in gas generator breech
T_U	–	Gas temperature in accumulator
T_{TK}	–	Liquid temperature in accumulator
T_∞	–	Environmental chamber temperature

3.5.2.3 Test Procedure

The basic test procedure for characterizing the performance of the solid propellant pressurization subsystem was as follows:

1. Install proper liquid flow control orifice in accumulator
2. Install new (1,000-psid) burst disc in liquid flow outlet of accumulator
3. Install ignitor in gas generator
4. Install solid propellant cartridge in gas generator
5. Adapt gas generator to accumulator
6. Load liquid into accumulator
   a. Open vent valve
   b. Evacuate through accumulator fill valve
   c. Back fill with liquid until piston "tops out" on upper closure end of accumulator
   d. Shut fill and vent valves
7. Attach instrumentation
8. Install proper hot gas bleed orifice in outlet of hot gas control valve
   a. Ambient and +160°F soak conditions only

TEST SET-UP: BREADBOARD SOLID PROPELLANT PRESSURIZATION SUBSYSTEM



9. Hook up ignitor power leads
10. Soak to required operating temperature — hold 4 hours (minimum) after all temperatures indicate stable readings at required temperature
11. Start recorders
12. Fire gas generator
    a. Open bleed, as/if required after P_c ignition peak.

3.5.2.4 Expulsion Test Results

Eighteen solid propellant cartridges were fired to obtain the required ignitor performance; define gas generation rate versus operating pressure level at -65, ambient, and +160°F operating conditions; and to evaluate the proposed hot gas bleed technique.

Fuel expulsion at -65°F soak conditions was simulated by substituting isopropyl alcohol for the TSF-2 fuel mix. Fuel expulsion at ambient and +160°F soak conditions was simulated by substituting water for the fuel blend. One test was conducted expelling TSF-2 fuel at ambient soak conditions.

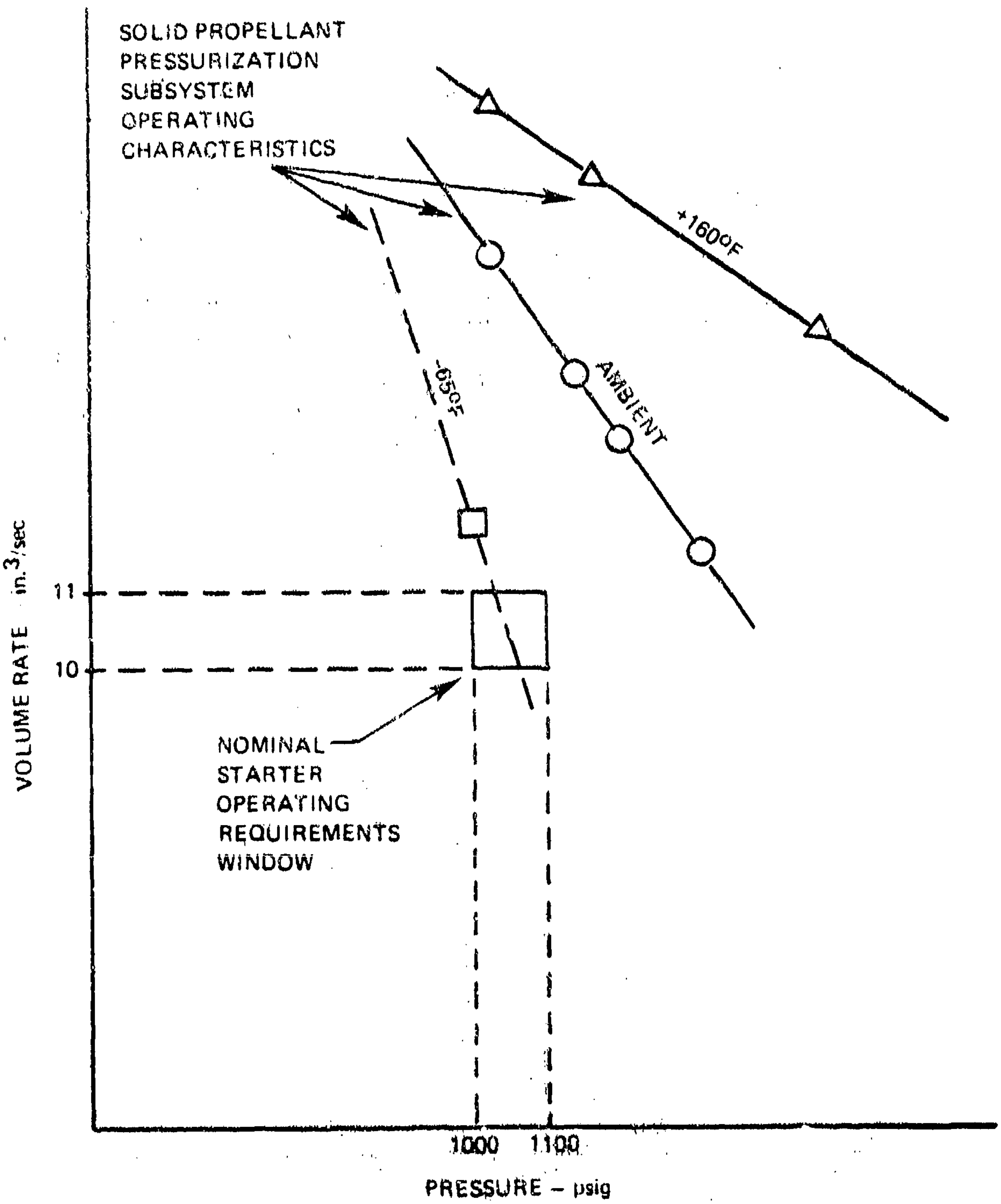
The test results are summarized in Figures 68 and 69. Figure 68 is an overlay of the nominal starter fuel supply requirements and the operating characteristics of the solid propellant pressurization subsystem at -65, ambient, and +160°F soak conditions. Referring to Figure 68, the nominal starter fuel supply requirements can be depicted by a window bounded by a fuel volume rate of 10 to 11 in.^{3}/sec and a fuel supply pressure of 1,000 to 1,100 psig. The operating characteristics of the solid propellant pressurization subsystem are defined by plotting the rate of gas generated as a function of breech pressure at -65, ambient, and +160°F soak conditions. The required solid propellant subsystem operation is obtained if the gas generating rate passes through the starter requirements window at -65, ambient, and +160°F soak conditions.

Referring to Figure 68, it will be noted that the operating characteristics of the solid propellant subsystem are acceptable at -65°F soak conditions; i.e., the rate of gas generation at the required starter operating pressure level falls within the boundaries of the window. Further, it will be noted that the operating characteristics of the solid propellant pressurization subsystem are unacceptable at ambient and +160°F soak conditions since these operating lines do not pass through the starter requirements window. The rate of gas generation, at these temperature conditions, exceeds the volumetric rate of starter fuel consumption at the required fuel supply pressure.

As noted in paragraph 3.5.1, this trend of excess gas generation with increasing subsystem operating soak temperature was anticipated and is consistent with the use of a propellant blend with a higher value of π_k than desired.

The effective value of the rate of gas generation for the solid propellant subsystem can be reduced (at ambient and +160°F soak conditions) to a level consistent with the starter requirements window by bleeding off a small amount of the gas being generated. The amount of gas bleed is small, since

OPERATING CHARACTERISTICS (NO BLEED)



SOLID PROPELLANT SUBSYSTEM OPERATING CHARACTERISTICS (WITH – BLEED)

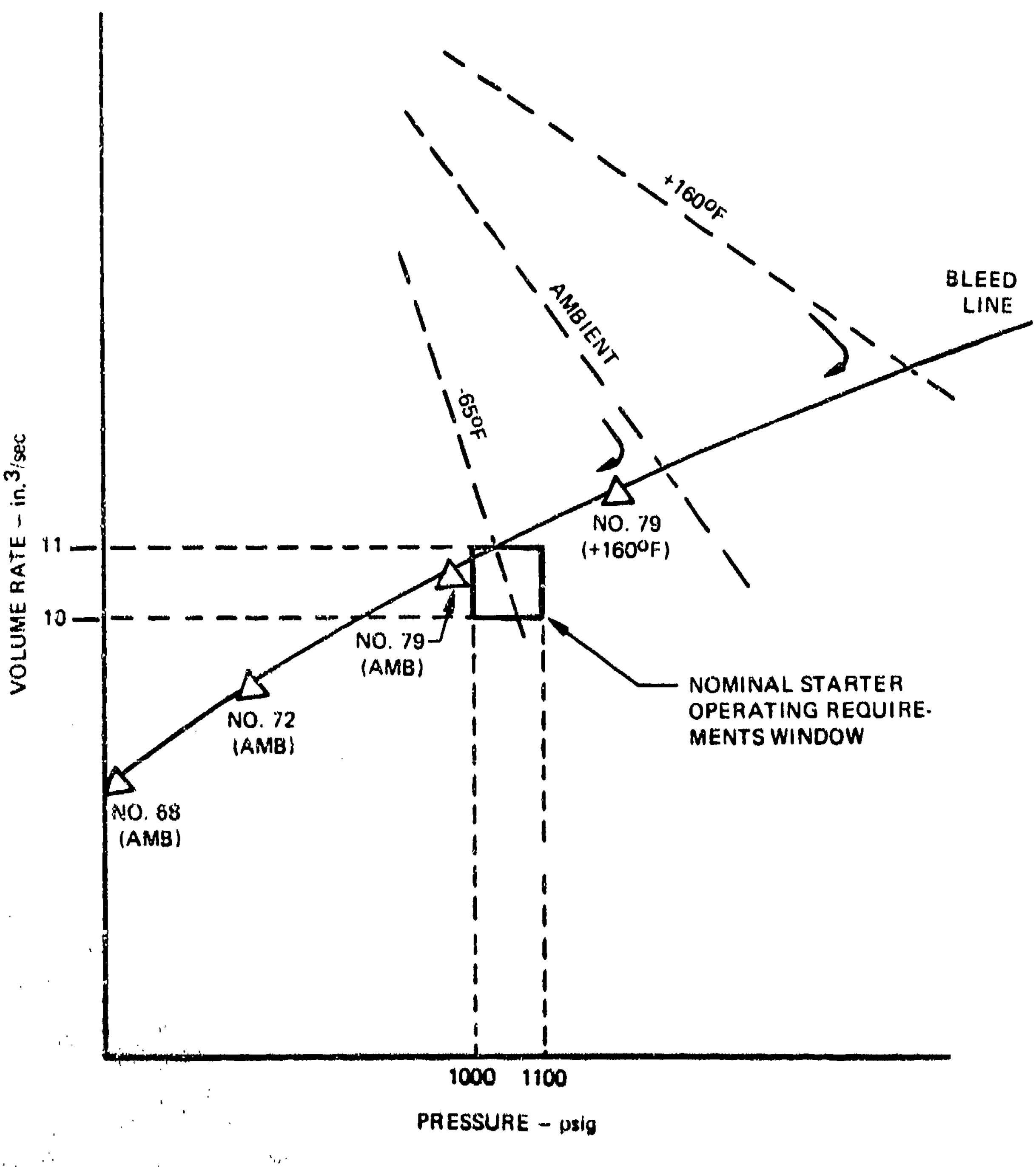


Figure 69

gas bleed reduces the burning pressure which in turn reduces the rate of gas generation (Equation 7, paragraph 3.5.1).

Figure 69 depicts the feasibility of using the solid propellant pressurization subsystem, with bleed, to satisfy the starter fuel supply requirements. At -65°F soak conditions, the pressurization subsystem (as sized and tested in this program) operating line passes through the starter requirements window with no bleed. At ambient soak conditions, hot g[illegible]d through a number 68 drill orifice dumps too much gas; hot gas bleed through a numbe[illegible]ll orifice dumps too much gas; hot gas bleed through a number 79 drilled orifice comes very close to the nominal starter requirements window. Likewise, hot gas bleed through a number 79 drill orifice reduces the effective gas generating rate at +160°F soak conditions to a level that is very close to the starter requirements window.

3.5.3 Hydrazine Starter Operation With Breadboard Solid Propellant Subsystem Fuel Supply

As a final feasibility demonstration of the hydrazine-fueled starter concept, RRC has successfully conducted three full-power starter operating cycles, at ambient soak conditions, using the breadboard solid propellant pressurization subsystem, with bleed, for fuel supply.

The test setup is shown schematically in Figure 70 and pictorially in Figure 71. Referring to Figure 70, the starter was mounted on the universal test stand, and the flight concept gas generator (eight-cup GG) was installed in the breech base. The breadboard solid propellant fuel supply subsystem was adapted to the gas generator through a check valve and a normally closed solenoid valve as shown. The breadboard fuel expulsion device was loaded with TSF-2 fuel, and the solid propellant cartridge and ignitor were installed in the gas generator breech. A number 79 drill bleed orifice was adapted to the solid propellant gas generator through a normally closed solenoid valve.

Starter operation involved the following:

a. Apply 28-vdc power to the ignitor.

b. Simultaneously open the solenoid valves in the main gas generator fuel supply and hot gas bleed lines.

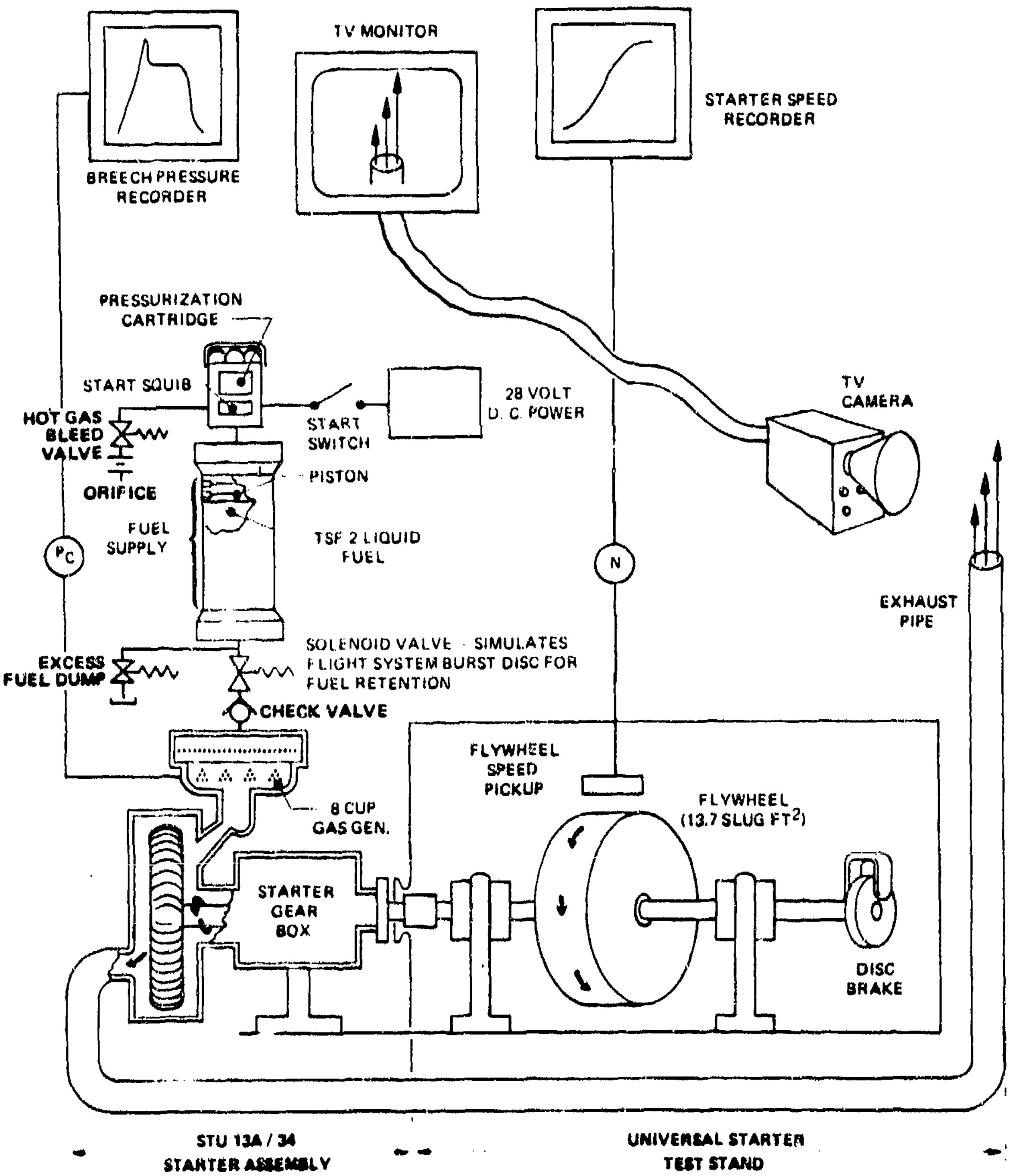
   NOTE: Simulates the rupture of burst discs in the flight concept design.

c. When the required flywheel terminal speed is achieved, open the solenoid valve that is installed in the fuel outlet bypass of the breadboard fuel accumulator (dump excess fuel).

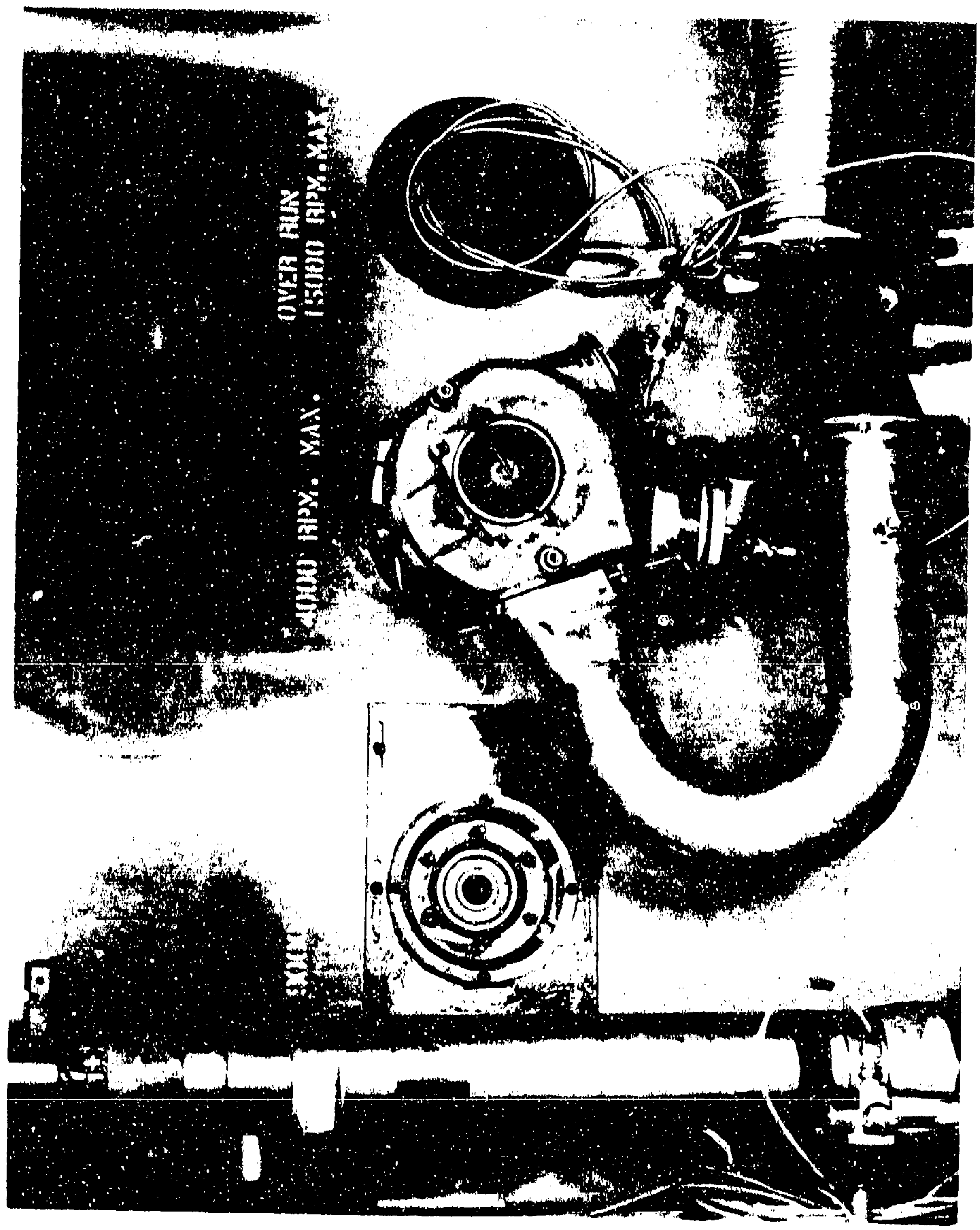
   NOTE: The accumulator in the breadboard fuel supply subsystem has a fuel capacity of 370 in.^{3} which exceeds the required fuel volume of 186 in.^{3} by a considerable margin. Thus the excess fuel was dumped to avoid starter overspeed for the breadboard system test firings.

The operating characteristics of the hydrazine-fueled starter, operating in conjunction with the breadboard solid propellant pressurization fuel supply subsystem, are shown in Figure 72.

TEST INSTALLATION
HYDRAZINE MODE
AIRCRAFT JET ENGINE STARTER DEMO.



HYDRAZINE FUELED STARTER TEST INSTALLATION
– FORMAL DEMONSTRATION



TYPICAL AMBIENT STARTER OPERATING CHARACTERISTICS
SOLID PROPELLANT PRESSURIZED
HYDRAZINE MODE

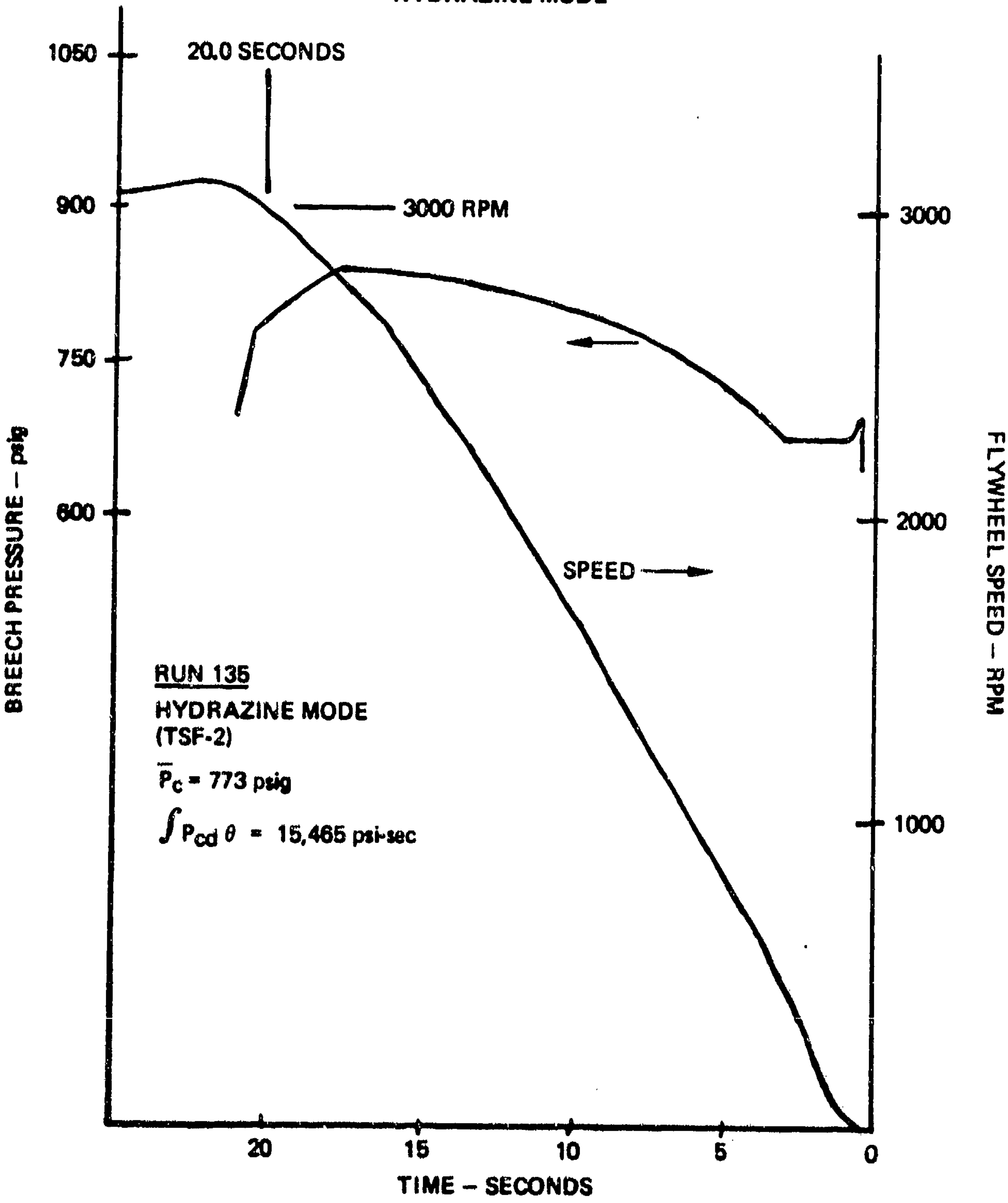


Figure 72

SECTION IV
FINAL FLIGHT CONCEPT PRELIMINARY DESIGN

The final flight concept preliminary design version of the hydrazine starter is shown in Figures 73 through 78. Major components of the system include:

a. The starter gas generator
b. An expendable hot gas bleed burst disc insert
c. The liquid fuel cartridge.

A brief description of the major system components follows.

4.1 STARTER GAS GENERATOR

The starter gas generator is an assembly of eight, axial-flow gas generating elements arranged in parallel and manifolded to a central fuel supply fitting. Each of the eight gas generating elements consists of an outer shell (cup) loaded with 20.5 grams of Shell 405 spontaneous catalyst (25- to 30-mesh granules). The catalyst is retained in the cup by a slotted bedplate and a bedplate retaining ring. The retaining ring is welded to the outer shell after catalyst loading. Fuel is introduced into the catalyst bed in a radial direction through four 0.044-inch-diameter holes in an injector stub that penetrates approximately 0.2 inch into the upstream end of the catalyst bed. A wire mesh screen is used to prevent catalyst particle migration into the 0.044-diameter injector ports.

With the exception of the screen, all starter gas generator components are fabricated from 300 series stainless steel. Each of the eight gas generating elements, the injector stubs, and the fuel manifolding tubes is brazed to the mounting structure with Palniro I braze material.

4.2 HOT GAS BLEED - BURST DISC INSERT

As discussed in paragraph 3.5, there is a requirement to bleed excess gas generated by the solid propellant pressurization subsystem at ambient and +160°F operating conditions. This requirement can be satisfied by placing a bleed orifice across the starter gas generator mounting plate and controlling the flow of breech gas through the bleed orifice by means of a burst disc. The burst disc would be designed to rupture at a predetermined pressure differential between the breech and the turbine inlet pressures. The burst disc would be designed to remain intact at -65°F breech pressure, thus preventing breech gas bleed at -65°F operating conditions. The burst pressure would be selected to provide gas bleed at any operating temperature above approximately 40°F (RRC estimate).

The hot gas bleed passage would not be open at -65 to +40°F operating conditions during starter operation. However, when the fuel is consumed after a normal starter operating sequence in this temperature range, the starter gas generator outlet pressure (turbine inlet pressure) will decrease to local ambient pressure: and the hot gas bleed burst disc will rupture due to the high pressure differential that exists between the pressurized breech and the unpressurized breech base cavity. Burst disc rupture will vent the breech cap and allow access to the expendable fuel cartridge.

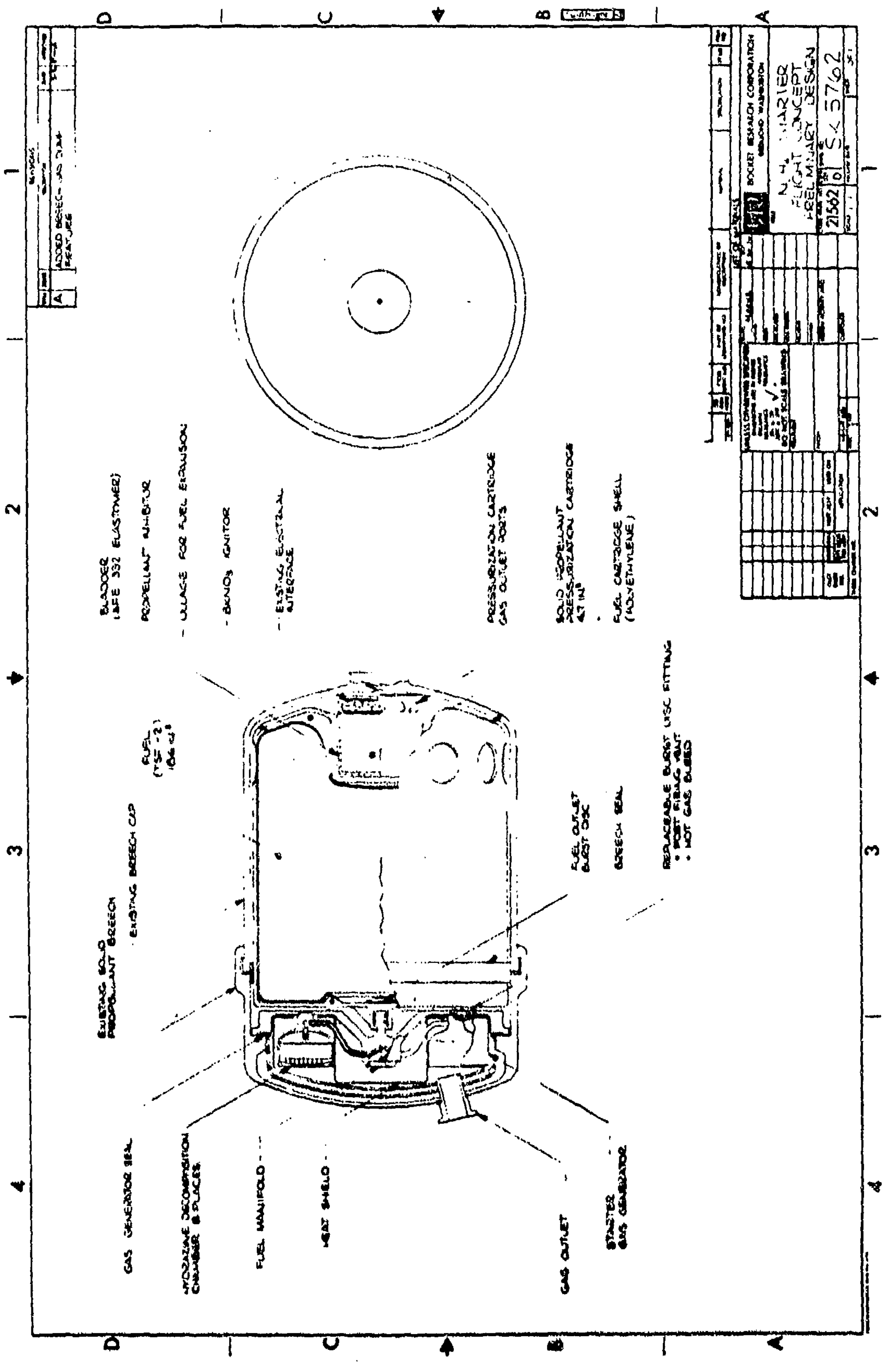
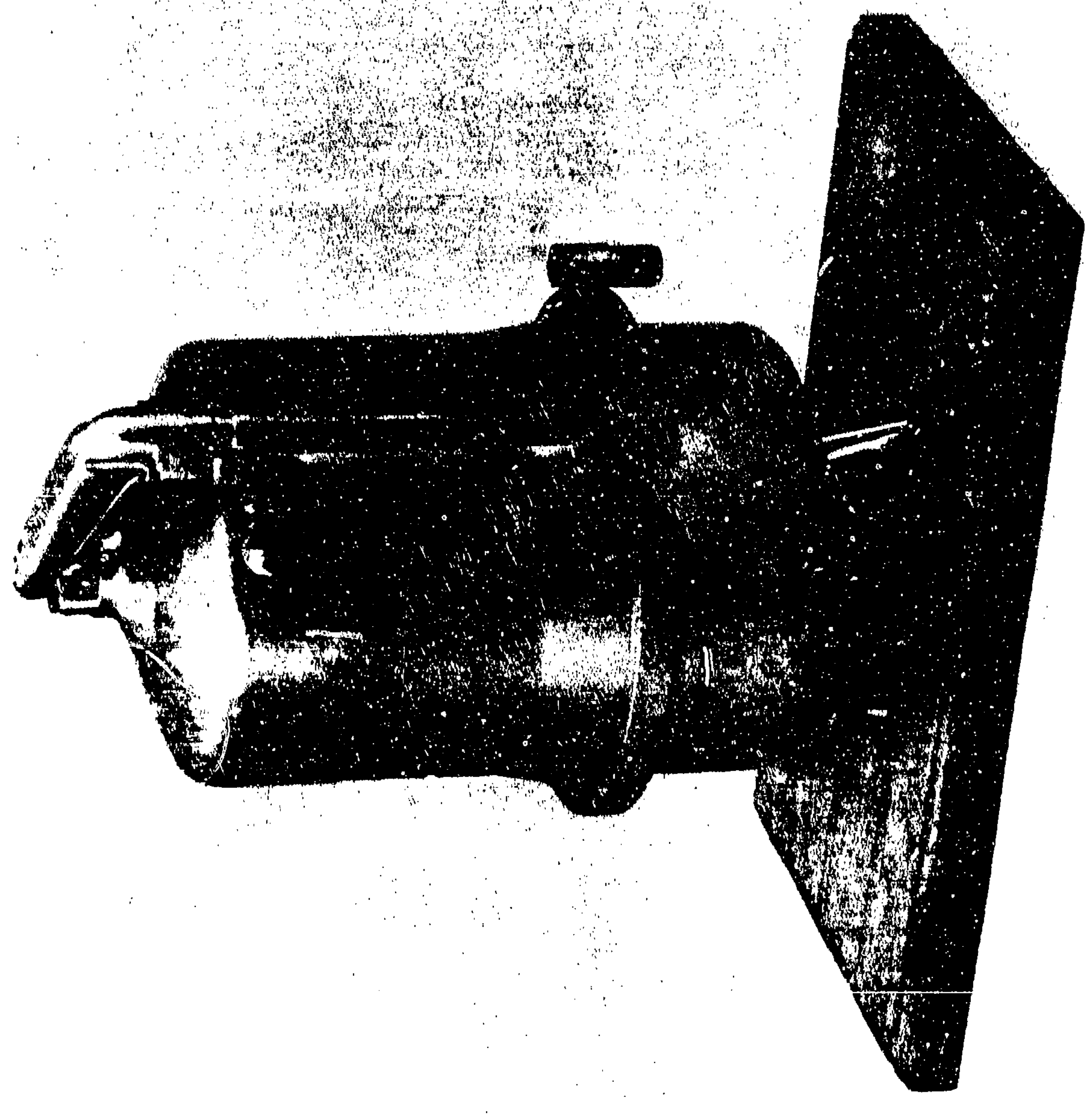
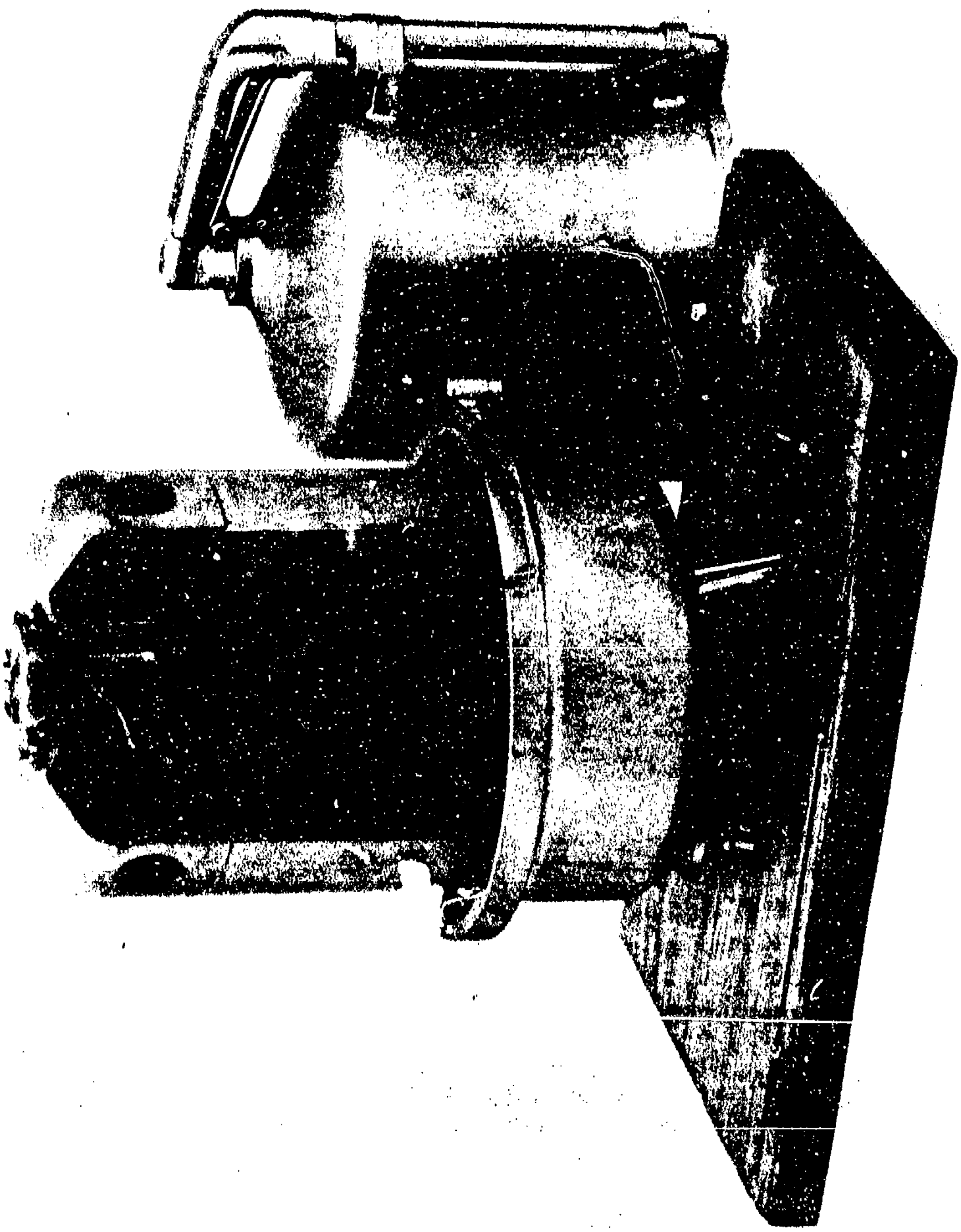

EXISTING SOLID PROPELLANT BREECH
EXISTING BREECH CAP
BLADDER (AFE 332 ELASTOMER)
PROPELLANT INHIBITOR
ULLAGE FOR FUEL EXPANSION
EXISTING ELECTRICAL INTERFACE
PRESSURIZATION CARTRIDGE GAS OUTLET PORTS
SOLID PROPELLANT PRESSURIZATION CARTRIDGE
FUEL CARTRIDGE SHELL (POLYETHYLENE)
FUEL OUTLET BURST DISC
BREECH SEAL
REPLACEABLE BURST DISC FITTING
GAS GENERATOR SEAL
HYDRAZINE DECOMPOSITION CHAMBER 8 PLACES
FUEL MANIFOLD
HEAT SHIELD
GAS OUTLET
STARTER GAS GENERATOR
ROCKET RESEARCH CORPORATION
PRELIMINARY DESIGN
SK 5762

Figure 73



HYDRAZINE STARTER MOCKUP (SK 5762)

HYDRAZINE STARTER MOCKUP (SK 5762)



HYDRAZINE STARTER MOCKUP (SK 5762)

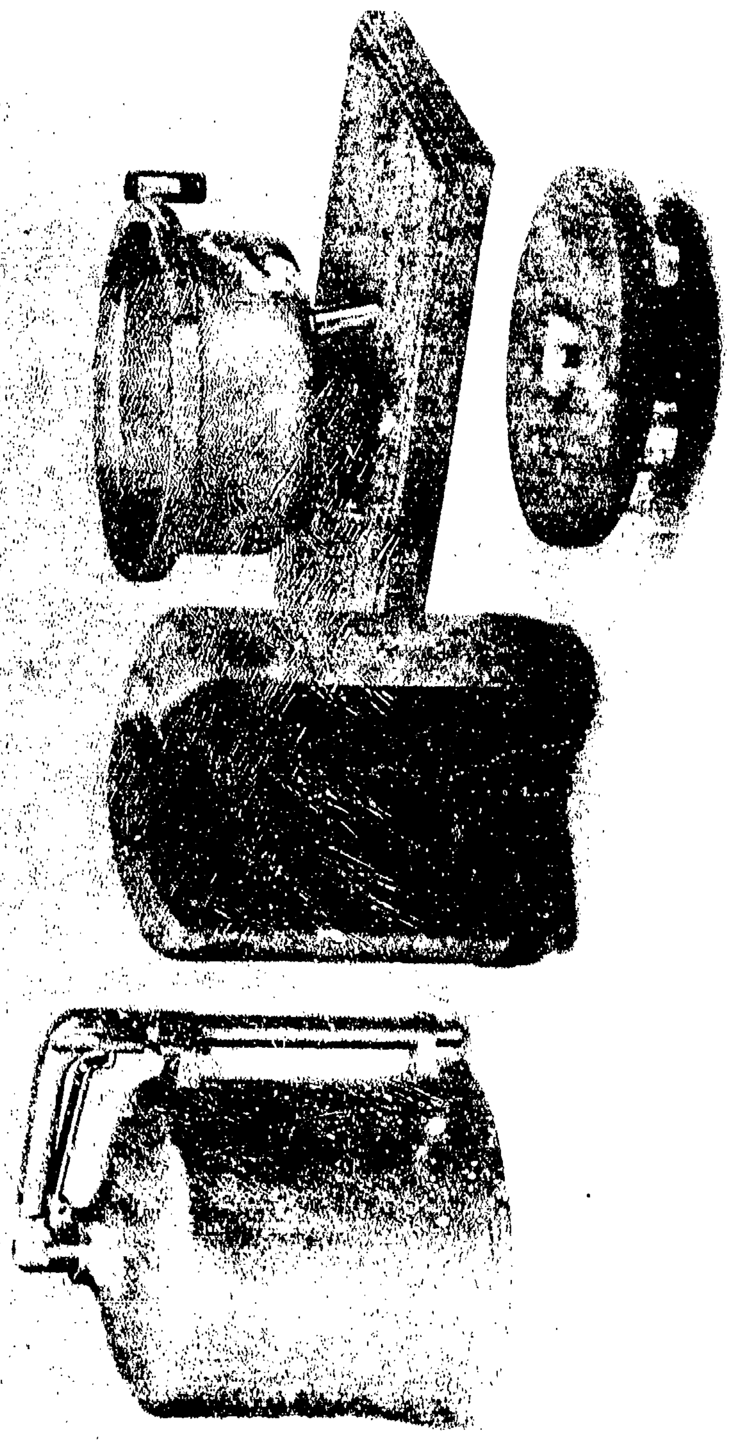
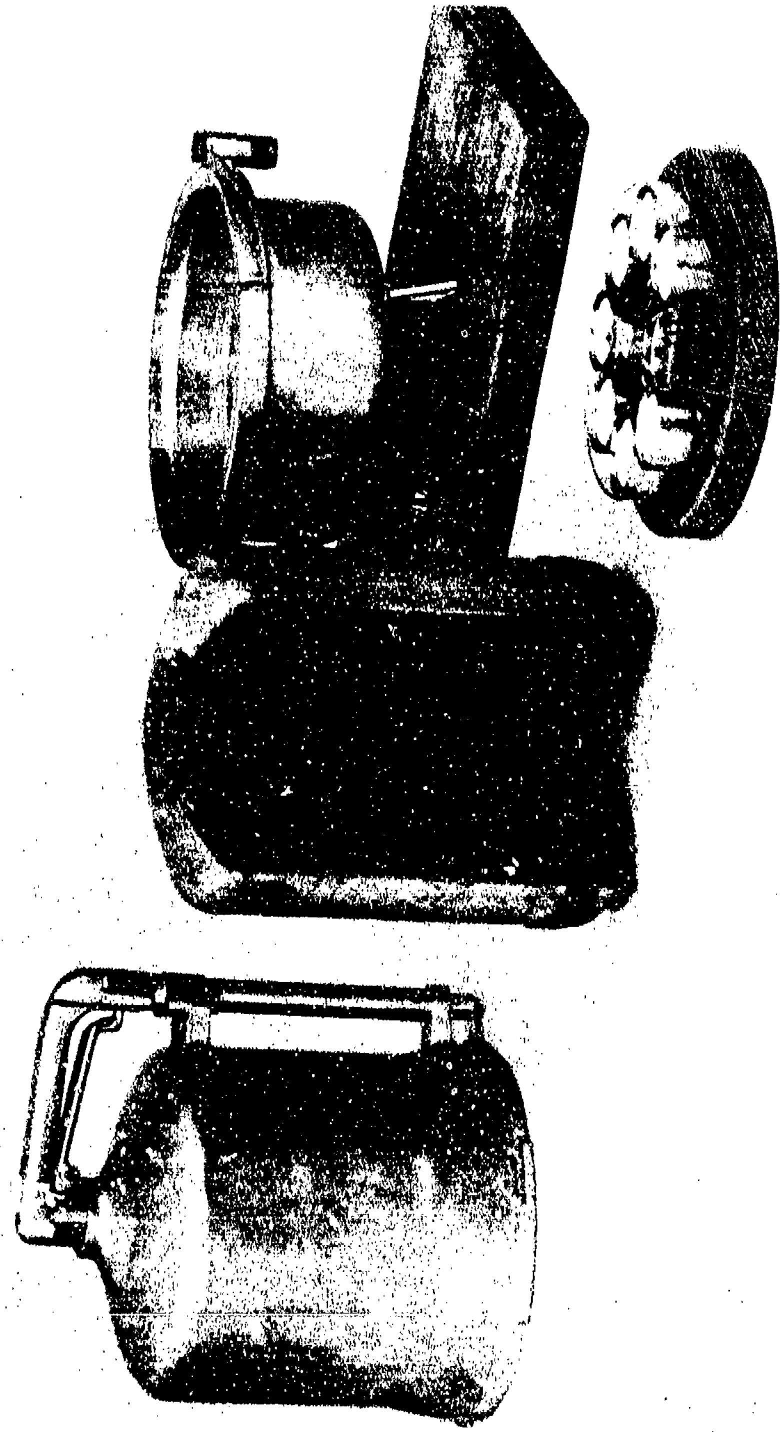
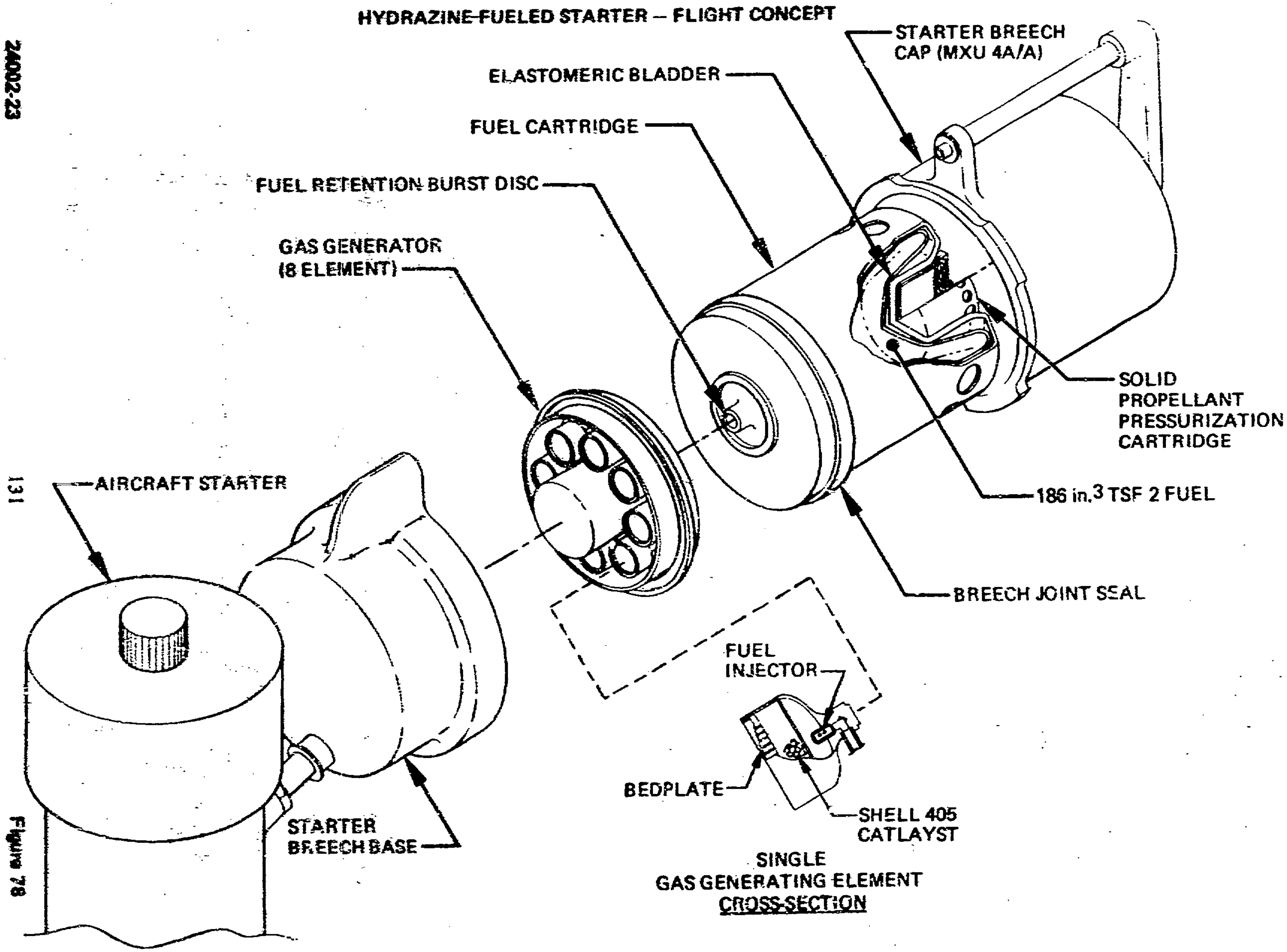


Figure 76

HYDRAZINE STARTER MOCKUP (SK 5762)





24002-23

Figure 78

Breech cap venting will occur automatically through the open hot gas bleed orifice at fuel depletion at system operating temperatures in the +40 to +160°F range. Thus, the hot gas bleed insert is an expendable item that is replaced, with the liquid fuel cartridge, after each starter operating cycle.

4.3 LIQUID FUEL CARTRIDGE

The fuel cartridge is an assembly of the outer shell, fuel retention bladder, the liquid fuel charge, and the solid propellant pressurization cartridge.

The outer shell is an injection-molded polyethylene structure that provides handling protection to the liquid fuel charge. The outer shell contains provisions for fuel bladder retention, interfacing features for the fuel supply to the starter gas generator, and retention of the solid propellant pressurization cartridge. The fuel cartridge will contain 7.71 pounds of TSF-2 fuel. The fuel blend is contained by a combination of the polyethylene fuel shell, an elastomeric bladder, and a fuel outlet burst disc.

The solid propellant pressurization cartridge is a hermetically sealed subassembly that would be packaged in a light-gauge metal can, which in turn would "snap in" to the outer shell of the fuel cartridge. The pressurization cartridge is an assembly of the outer can, the solid propellant grain, ignitor, and the electrical interfacing connector for the ignitor. The electrical power interface with the breech cap is identical to that presently used in the standard MXU4A/A solid propellant starter cartridge.

The solid propellant grain is an end burning configuration 2.1 inches in diameter and 1.5 inches in length. The grain is inhibited on the cylindrical surface and one end. The propellant is a gum rubber/ammonium nitrate blend designated as TAL 431MOD 0.076 and is identical to that currently used in late model MXU4A/A starter cartridges manufactured by Talley.

4.4 FLIGHT LINE HANDLING REQUIREMENTS

The flight line handling requirements associated with the flight concept version of the hydrazine-fueled starter, as described in this section, would be very similar to the current MXU4A/A solid propellant cartridge handling requirements.

The main gas generator would be permanently installed in the starter breech base, requiring no flight line maintenance.

The liquid fuel cartridge would be changed prior to starter operation by removing the breech cap, removing the spent cartridge, and installing a fresh cartridge as is presently done with the MXU4A/A solid propellant cartridge.

There would be one additional task for the flight line mechanic. The hot gas bleed burst disc insert would have to be removed and replaced. The removal and replacement of this device could be eliminated by further design effort which would integrate the feature into the liquid fuel cartridge external shell structure.

SECTION V
CONCLUSIONS

The feasibility of converting a jet engine cartridge starter to operate successfully and acceptably with monopropellant hydrazine has been demonstrated. The ability to package the complete hydrazine subsystem (conversion package) within the space normally occupied by the standard 8-lbm type MXU4A/A solid propellant cartridge is a readily obtainable goal.

The breadboard version of the hydrazine-fueled jet engine starter has been successfully demonstrated over the required -65 to +160°F operating range. Starter performance equal to or exceeding the current solid-propellant-fueled starter has been demonstrated. The flight concept type (eight-cup) gas generator has been used to conduct 35 full-power hydrazine-fueled starter operating cycles with no detectable performance degradation which would be indicative of gross catalyst bed life limitations.

There are several features of the hydrazine-fueled starter concept that can be classified as potential improvements to the current solid-propellant-fueled cartridge starter. These features include:

a. Particulate free exhaust. There is no smoke; this would result in improved flight line visibility during cartridge starter operation.

   Additionally, the lack of solid particles in the hydrazine exhaust means that there is no particulate buildup in the hot section of the starter. Particulate buildup as experienced with the MXU4 type solid cartridge reduces turbine performance and is the driving factor in the corrosion of all components in the hot section of the starter.

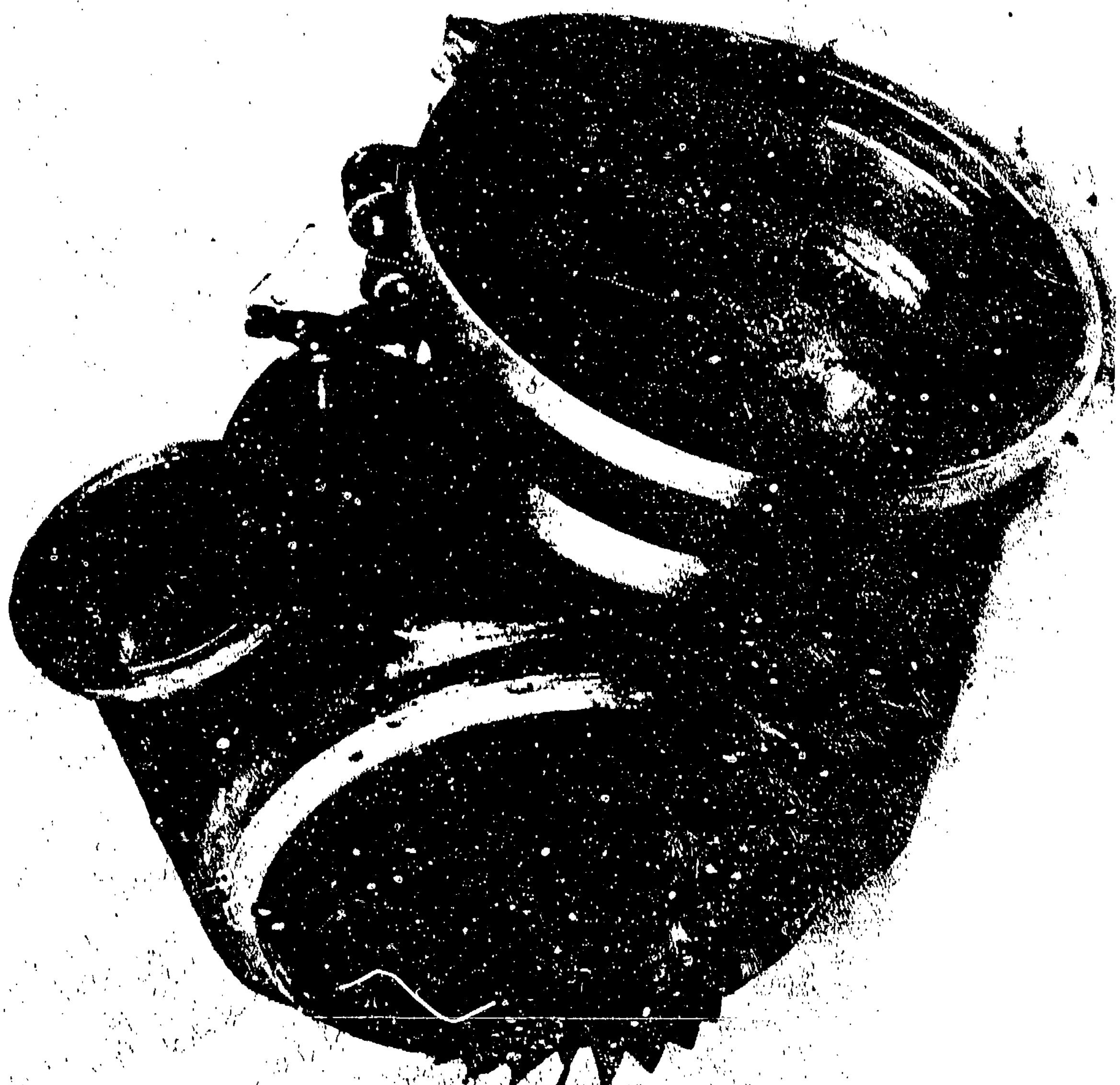
b. Turbine inlet temperatures are 200 to 500°F lower with the hydrazine-based fuel blend as compared to the temperatures measured during starter operation in the cartridge mode. Lower turbine inlet temperatures are conductive to extended turbine wheel life.

   The combined effect of items a. and b. above would have a strong influence on starter life. Rocket Research Corporation estimates that the time between overhaul requirements could be increased from the current value of 30 to 300 starts for the solid-propellant-fueled starter to a value approaching 2,000 starts for the hydrazine-fueled starter.

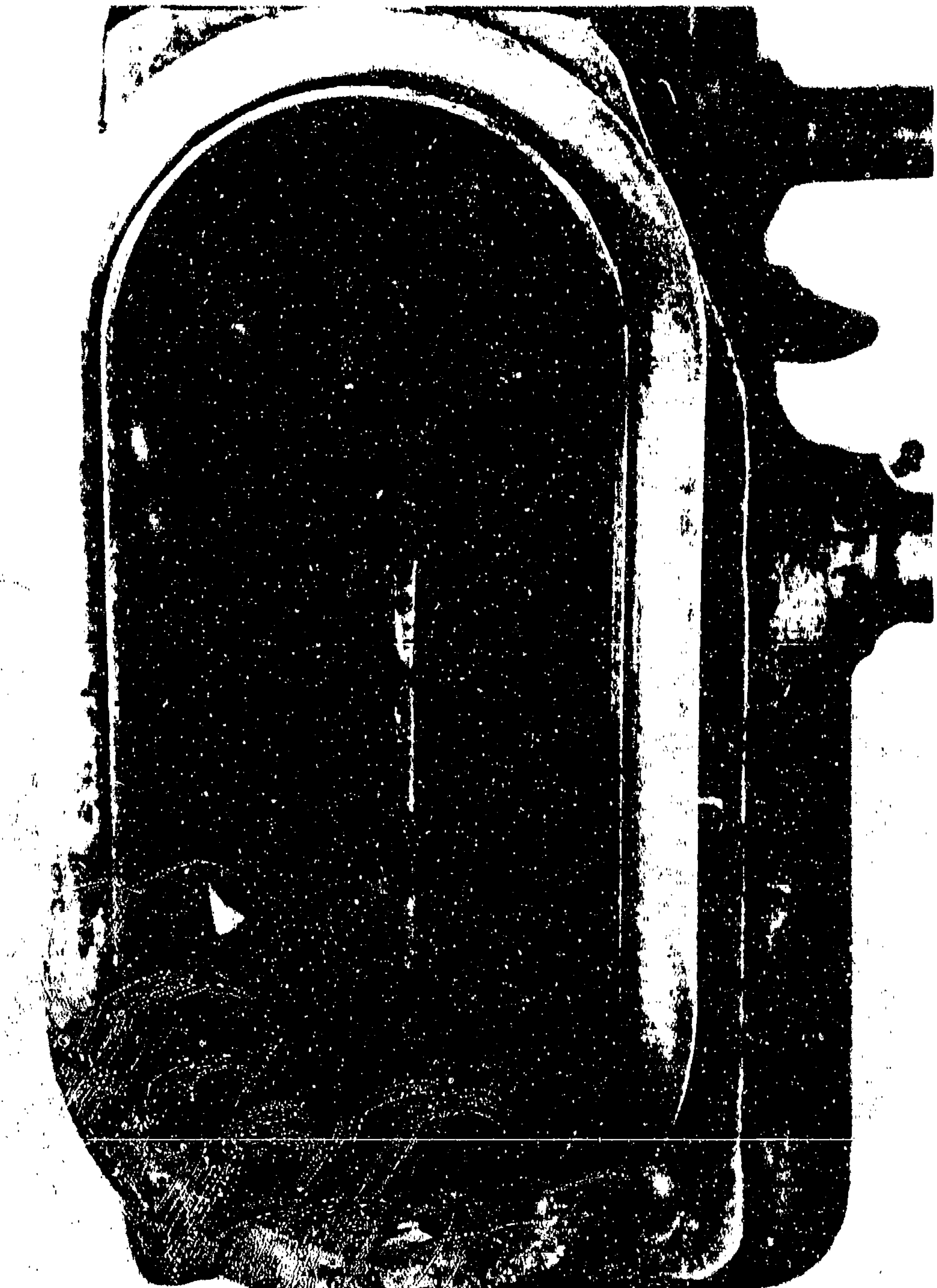
c. The flammability and toxicity of the hydrazine exhaust products are no worse than those obtained from the MXU4A/A solid propellant cartridge exhaust.

Figures 79 through 81 depict the condition of the hydrazine-fueled starter after 35 full-power operating cycles. There is no residue or particulate buildup on any starter component.

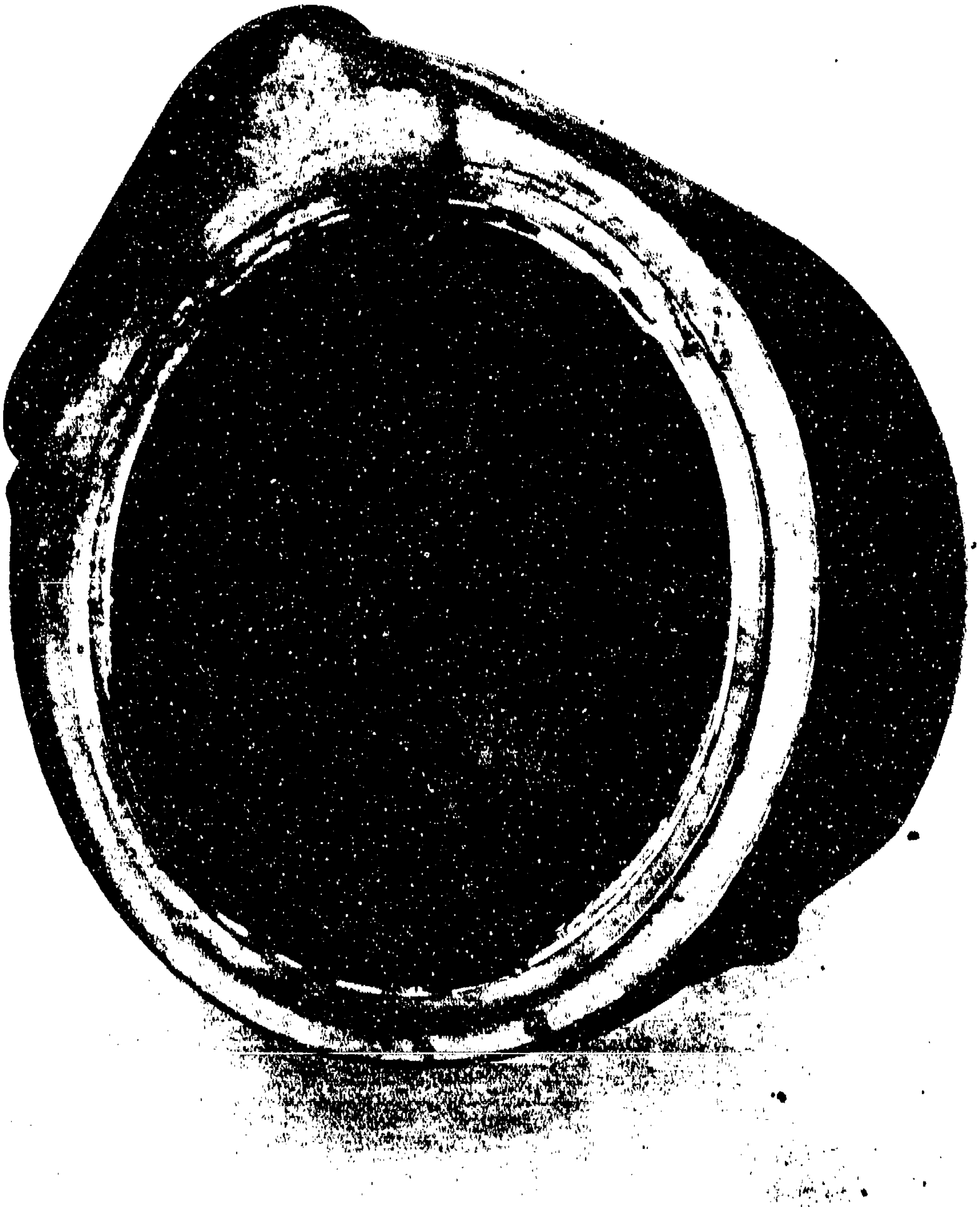
Figures 82 through 85 are photographs of a typical cartridge starter, as received at the overhaul center (ALC, Kelly AFB), after accumulating an unknown number of cartridge starts. The difference in cleanliness between both starters is obvious.



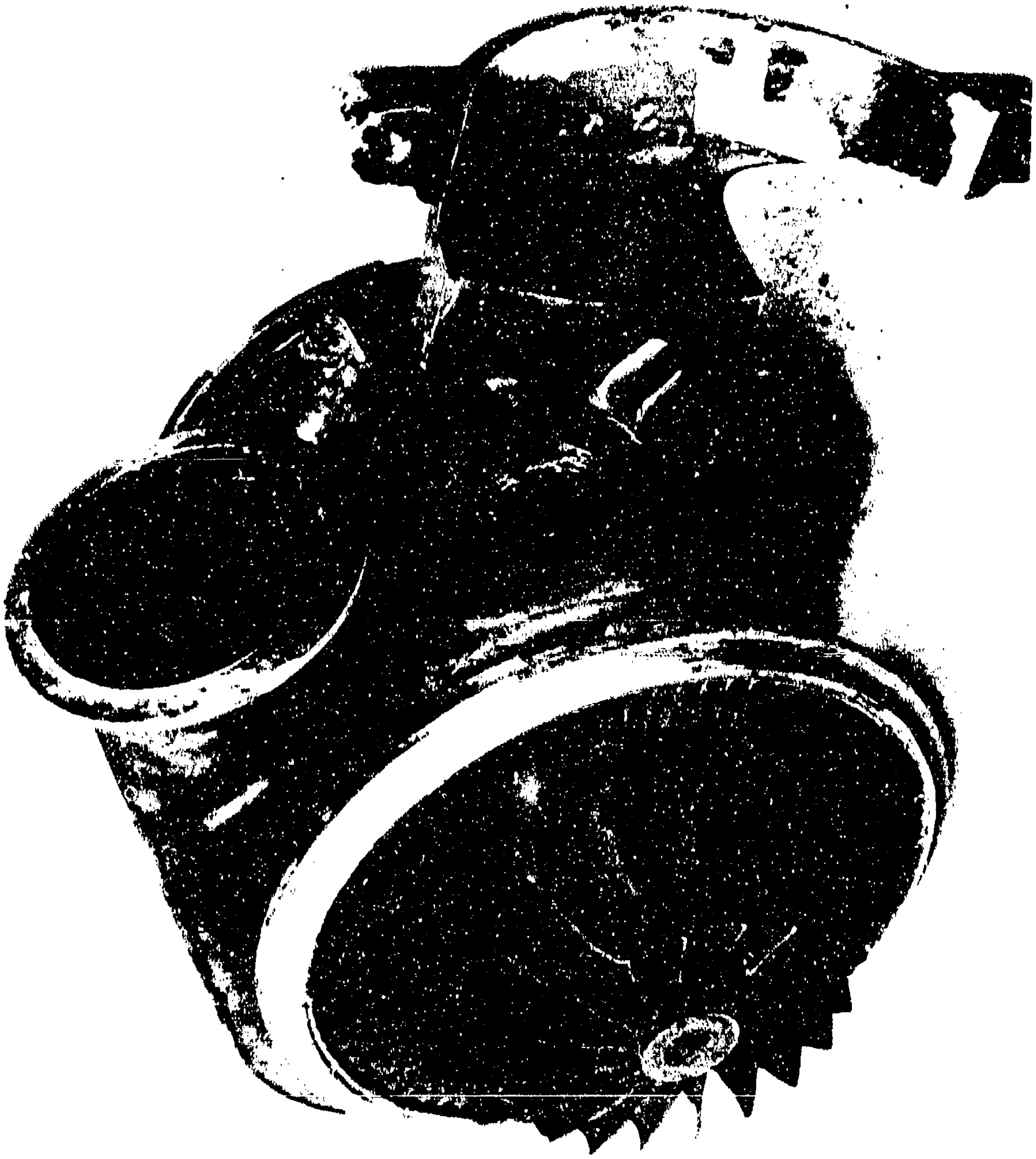
HYDRAZINE-FUELED STARTER AFTER 35 FULL POWER STARTS



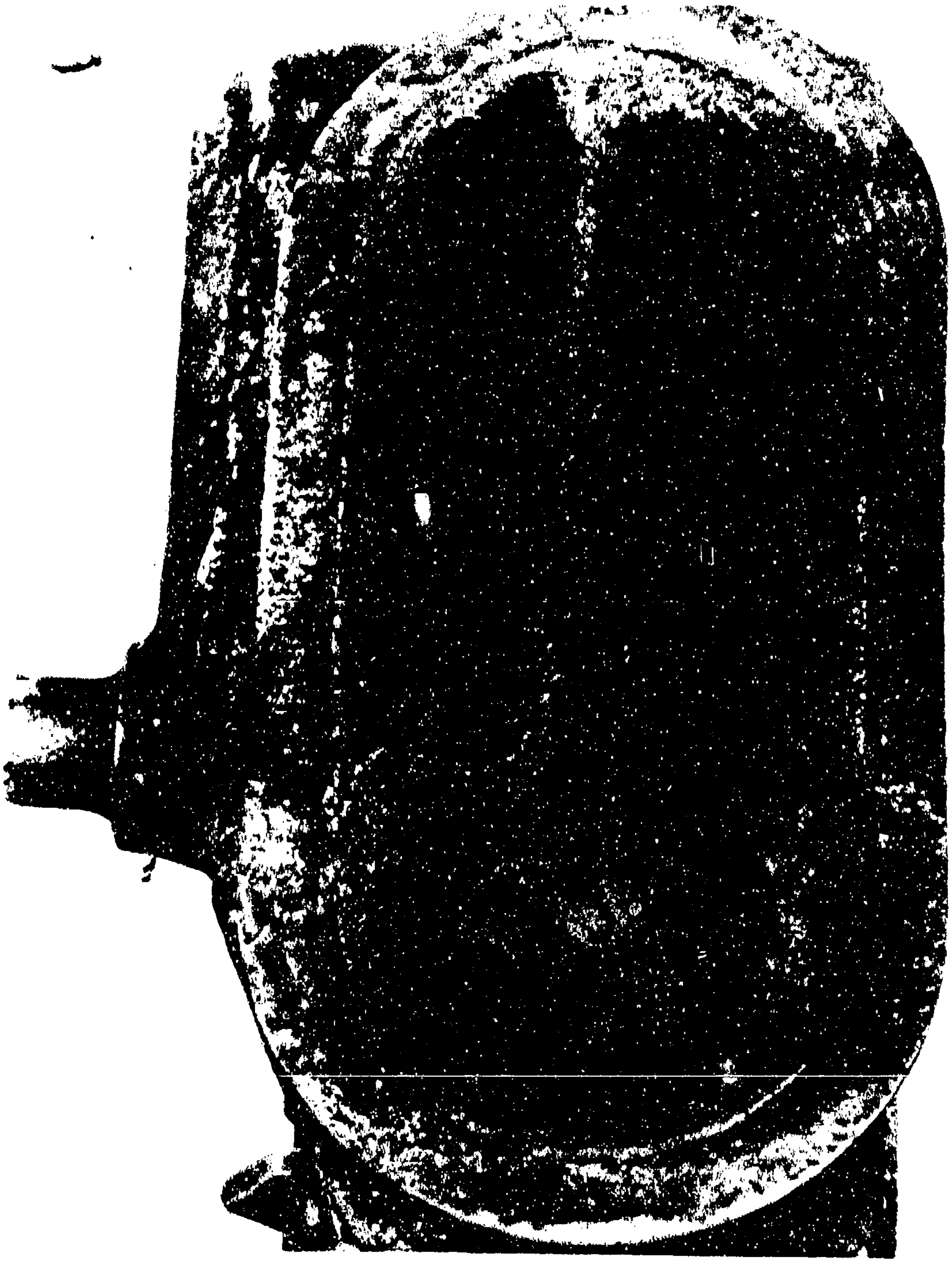
HYDRAZINE-FUELED STARTER
(TURBINE EXHAUST MANIFOLD)
AFTER 35 FULL POWER STARTS



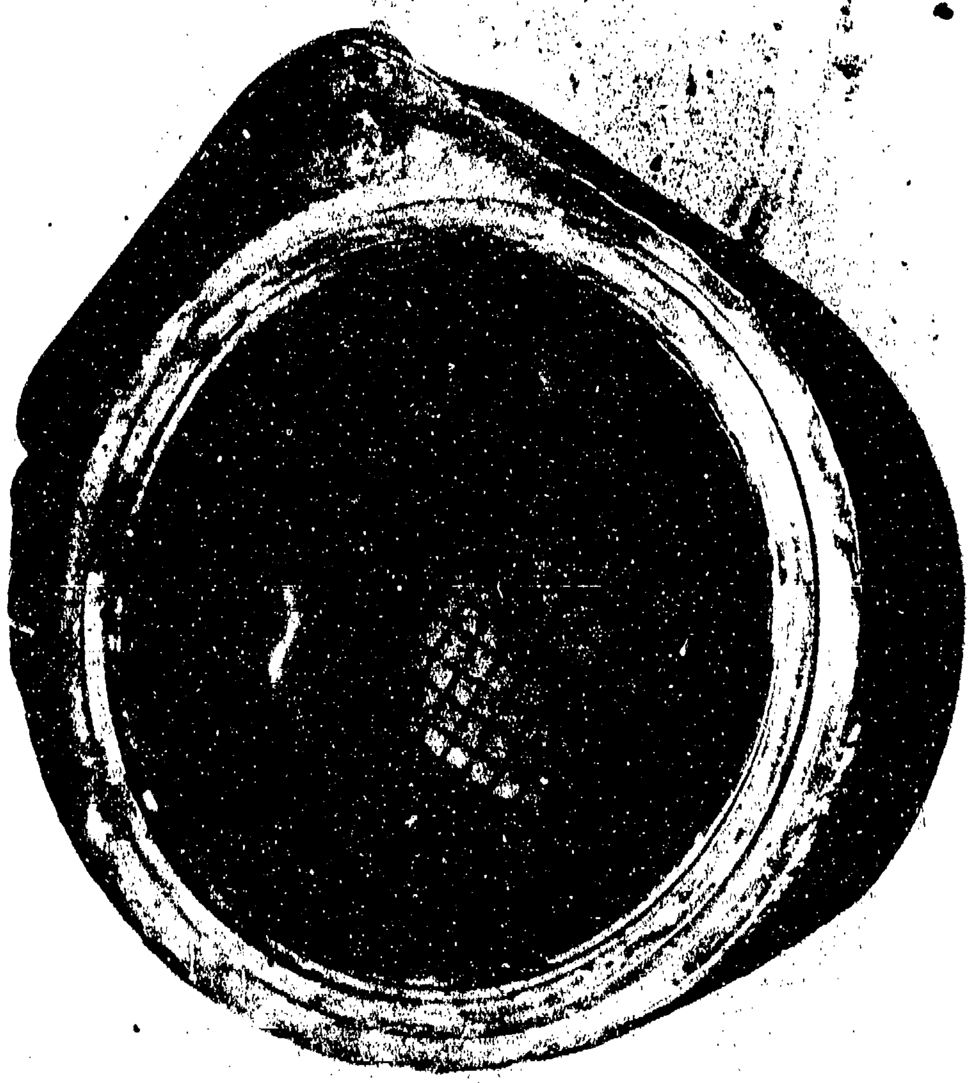
HYDRAZINE-FUELED STARTER
(TURBINE EXHAUST MANIFOLD)
AFTER 35 FULL POWER STARTS



CARTRIDGE STARTER AS RECEIVED FOR ALC OVERHAUL
(NUMBER OF STARTS UNKNOWN)



CARTRIDGE STARTER AS RECEIVED FOR ALC OVERHAUL
(TURBINE EXHAUST MANIFOLD)
NUMBER OF STARTS UNKNOWN



CARTRIDGE STARTER AS RECEIVED FOR ALC OVERHAUL
(TURBINE EXHAUST MANIFOLD)
NUMBER OF STARTS UNKNOWN

CARTRIDGE STARTER AS RECEIVED FOR ALC OVERHAUL (BREECH BASE)
NUMBER OF STARTS UNKNOWN

In closing, it should be noted that a considerable portion of the time and funds expended on this program were related to solving the unique problems associated with the packaging of the entire hydrazine conversion subsystem into the space that is normally occupied by the 8-lbm MXU4A/A solid propellant cartridge. Additionally, little if any problems were associated with the development of the gas generator that was used to power the starter. Future aircraft starter applications may warrant consideration of hydrazine and particularly so if the aircraft has a central hydrazine fuel supply system for other auxiliary apparatus.

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